FEDERAL/PROVINCIAL
RESEARCH AND MONITORING
COORDINATING COMMITTEE (RMCC)

ASSESSMENT OF THE STATE OF KNOWLEDGE ON THE LONG-RANGE TRANSPORT OF AIR POLLUTANTS AND ACID DEPOSITION

PART 4

TERRESTRIAL EFFECTS

AUGUST 1986

ACID RAIN
PLUIES ACIDES

Province of British Columbia
Ministry of Environment

Gouvernement du Québec
Ministère de l'Environnement

Alberta
ENVIRONMENT

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Nova Scotia
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Ontario
Ministry of the Environment

Province of Newfoundland
Department of the Environment

Canada

70719

TERRESTRIAL ASSESSMENT ERRATUM

Page 4-51 The Effects of Acid Rain on Wildlife

Paragraph 1 should read as follows:

Over the past few years a strong relationship between atmospheric deposition of trace metal pollutants and tissue residues in terrestrial mammals has been reported throughout Scandanavia. Southern areas receive the highest concentrations of Pb and Cd as measured in both bulk precipitation and in lichens and mosses and similar patterns have been reported for concentrations in liver and kidney of domestic and wild herbivores (Gydesen _et al_. 1981; Frank _et al_. 1981; Mattsson _et al_. 1981; Froslie _et al_. 1985). In addition to deposition rates, both age and feeding habits influence the pattern of accumulation in these animals, with the highest values generally found in older animals While moose appear to accumulate some of the highest levels of Cd, Norwegian reindeer did not appear to have significant Cd concentrations, irrespective of collection site (Froslie _et al_. 1985). Although similar investigations have been initiated in North America, few published results are available at this time. Schlesinger and Potter (1974) reported accumulation of Pb and Cd in small mammals in Hubbard Brook, New Hampshire which was consistent with data indicating higher atmospheric deposition in montane ecosystems of the north-east United States.

The potential effects of maple dieback on forest birds and their insect prey is presently under investigation in southern Quebec. These effects should depend on the stage and severity of dieback as well as on the feeding niches of the different bird species. While some birds may initially benefit from the larger numbers of dead branches and trees in the affected forests (eg. pileated woodpecker, black and white warbler), declines in numbers of other species (eg. eastern wood peewee) have been found in recent surveys of dieback areas (Desgranges, in press).

References:

Desgranges, J.L. in press. Forest birds as biological indicators of the progression of maple dieback in Quebec. Proceedings of Workshop on "Birds as Bioindicators of Environmental Conditions" I.C.B.P. 19th World Conference, 14-21 June 1986, Queen's University, Kingston, Ontario, Canada.

Mattsson, P., L. Albanus and A. Frank. 1981. Cadmium and some other elements in liver and kidney from moose (_Alces alces_): Basis of dietary recommendations. Var Foda _33_(8-9); 335-345.

Schlesinger, W.H. and Potter, G.L. 1974. Lead, copper and cadmium concentrations in small mammals in the Hubbard Brook Experimental Forest. OIKOS _25_: 148-152.

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RMCC TERRESTRIAL EFFECTS SUBGROUP

AUGUST 1986

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ACKNOWLEDGEMENTS

Many individuals have spent a great deal of their time in the production of this Terrestrial Assessment of the Effects of Acid Rain document. This report could not have been completed without their authorship and editorial help. Because of the interaction among the scientists involved, it is not possible to attribute authorship to a specific individual except in certain cases. The following is a list of the contributors by section:

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Editing of the document was carried out by P.A. Addison and S.N. Linzon, co-chairmen of the Terrestrial Effects Sub-Group with assistance from G.D. Hogan.

EXECUTIVE SUMMARY

The purpose of the Canadian Assessment of the Current State of Knowledge of LRTAP is to provide a sound technical and scientific overview that can provide the basis for emission control strategies and to determine the effects of any control program. In order to achieve this purpose for the terrestrial sector, a single question was posed by the Terrestrial Effects Sub-group of the Federal/Provincial Research Monitoring and Coordinating Committee that would focus the report and assist policy makers.

"What is the evidence for LRTAP effects on the terrestrial ecosystem?"

The answer to this question is based on the literature and current activities of scientists as a whole, including, but not limited by, the results presented at the International Symposium on Acid Precipitation held at Muskoka in 1985.

The specification of environmental objectives applicable to Canadian forest resources is of paramount importance. In Canada, there are currently no objectives for wet or dry deposition or mixtures of pollutants. There are special difficulties associated with the dose / response research that has to be conducted to develop such objectives but the current work is promising.

The evidence that air pollutants can influence basic biochemical and physiological processes in plants is irrefutable. Although the mechanisms by which O_3 inhibits metabolic functioning resulting in growth reduction or tissue death is well understood, the same cannot be said for acid precipitation. Several hypotheses for the mode of action of acid precipitation on physiological processes exist but a significant amount of research is required before a definitive statement can be made.

Ozone and acid rain at the levels seen in eastern Canada have been shown to affect pollen viability in experimental conditions. The result of reduced viability is an increase in fruit abortion that has been observed in aspen. Visible foliar symptoms in tree species, on the other hand, required rain pH below 3.2 before they occurred in field experiments. This being the case, it is unlikely that visible injury to forest vegetation caused solely by acid deposition has been observed in the field. Ozone, on the other hand, at concentrations found in eastern North America, has been shown to produce visible symptoms and reductions in growth and yield on forest species in the United States. Although little is known of the O_3 concentrations in Canadian forests, the generally accepted pattern of reduced O_3 concentrations from south to north indicates that most of the productive forests in Canada (softwoods) are exposed to only low O_3 levels.

In the agricultural system, the effects of acid precipitation are similar to those seen in the forestry sector. Visible injury symptoms have been reported only once on a field grown crop exposed to ambient precipitation supplemented with simulated acidic rain. Simulated acid rain at pH 3.0 or below has been shown to cause sufficient injury in several crops that economic losses are likely. Crop response to simulated acid rain is both species and cultivar dependent. The effect of O_3 on crop plants is much better understood. Exhaustive lists of crop sensitivity to O_3 are available based upon hundreds of laboratory trials performed in North America and Europe. From these studies, environmental objectives for O_3 concentrations have been produced. Currently, field trials are attempting to test the validity of transferring laboratory derived objectives to field situations.

The closest situation in eastern Canada to the forest declines occurring in Europe and eastern United States is the decline of sugar maple in Quebec and Ontario. The complexity of environmental stresses in the forest system prevents attributing decline to any specific variable however, acid rain has been implicated as a contributing factor in particular locations in both provincial studies.

Regional-scale air pollution has been suggested as a contributing factor in the reduction of forest productivity both in Canada and elsewhere. Although pollutants have the potential for causing growth reductions as seen around strong pollutant point sources, there is still insufficient data to permit a definitive statement as to the influence of existing regional-scale pollution levels on the forests of Canada. Surveying the Canadian total of 161 million hectares of productive and accessible forest, only 28% (46 million hectares) are exposed to deposition in excess of 20 kg ha^{-1} yr^{-1} of wet sulfate. These areas in both British Columbia and east of Manitoba, however, are important forests near mills and markets (Rennie, 1986).

Substantial evidence indicates that lichens and mosses are both very sensitive to air pollution and accumulate pollutants. Field studies have shown that responses to pollutants occur both around strong point sources and in remote areas.

Generally, field experiments to investigate the effects of simulated acidic rain on crop yields have indicated that the occurrence of foliar injury on plants occurs at lower pHs than observed in greenhouse grown plants which are not hardened off. Repeated occurrences of rainfall of low pH (pH 3.0 or lower) during the growing season will increase the likelihood of visible injury to crop plants. Field experiments to investigate the effects of simulated acid rain on crop yields however, have suggested that foliar injury does not have a significant effect on harvested yield in most crop cultivars investigated. Ozone, on the other hand, has been shown to reduce yield of several crops, although most areas of Canada have not been assessed. It is apparent that if the

Canadian hourly criterion of 82 parts per billion (nL L^{-1}) was adhered to, virtually all current crop productivity losses would be eliminated.

Evidence to date indicates that acid deposition has the capability to enhance the leaching of base cations and the solubilization of Aluminum. These changes in the soil chemistry have negative effects on soil biological processes that are responsible for the long-term maintenance of forest vigor. In addition, substantial soil chemical changes have been demonstrated to have direct effects on tree growth and survival. Regional studies have not been able to demonstrate that these effects are widespread. Despite the lack of widespread soil chemical changes, areas of potential sensitivity to acidic deposition have been delineated for most of Canada based on a common set of key mapping criteria originating from laboratory soils experiments. The revealed high sensitivity areas assist in the locating of monitoring plots and provide locations where intensive terrestrial-aquatic ecosystem interactions can be most effectively studied.

Acid deposition has increased the cycling of nutrients in some of the forest ecosystems that have been examined in eastern Canada. In particular, accelerated leaching of foliar and soil base cations have been reported. The chemistry of water within the forest ecosystem, however, is still largely controlled by the cycle of nutrients between the vegetation and soil. The effect of the increased cycling on nutrient uptake by forests is unknown.

Current evidence of the impacts of long range air pollution on wildlife comes from aquatic habitat changes, specifically relating to the loss of food organisms such as fish and sensitive macroinvertebrates. There also appears to be subtle effects of acidification that influence tissue element concentrations and reproduction in birds. The effects of regional air pollution on wildlife are very subtle and primarily unknown.

A number of apparently discrete, but in reality not unrelated, hypotheses have been proposed to explain the forest decline phenomenon of Central Europe. Some observers have tried to extrapolate the central European situation to Canada, but the hypotheses are applicable only as possible mechanisms, should pollution and other conditions attain European characteristics. In the absence of clear changes in tree growth or soil properties in the Canadian forest attributable solely to regional air pollution, the difficulty would lie in isolating incipient pollution effects from those of climate and the cyclical nature associated with normal forest growth processes.

Research efforts have been, and continue to be oriented toward the development of methods to detect the subtle effects of pollution impingement. This cannot be accomplished without basic studies into the mechanisms of pollutant damage to terrestrial systems. New directions in

research are occurring in studies dealing with both direct and indirect effects on forests and crops. Studies have turned away from a simplistic concentration of wet acid sulfate deposition. There is increased concern with wet acid nitrate deposition, with ozone and volatile organics, with the accummulation of potentially toxic elements, and especially with the concept of multiple stress and the effects of air pollution in the context of the demands of management practices.

4.1. INTRODUCTION

The purpose of the Canadian Assessment of the Current State of Knowledge of Long Range Transport of Air Pollution (LRTAP) is to provide a sound technical and scientific basis for emission control strategies and to determine the effects of any control program. In order to achieve this purpose, the effects of LRTAP on the terrestrial system must be determined. The Terrestrial Effects Sub-Group (TESG) agreed to pose a single question around which each of the components of the terrestrial system could focus its discussion.

What is the evidence for LRTAP effects on the terrestrial system?

The mode of action for the assessment was to synthesize the reports presented at the International Conference on Acid Precipitation at Muskoka with these in the more widespread literature. This document is an assessment supported by references rather than a literature review. There have been several excellent literature reviews carried out in the last few years on many of the topics presented. In this assessment we have tried to minimize the size and the scientific and technical complexity as much as possible so that it will be of use to those originally envisaged as the end users - the policy makers.

4.2. ENVIRONMENTAL OBJECTIVES

4.2.1. **Why are Environmental Objectives Important?**

The experience gained from research on high gaseous concentrations of pollutants such as SO_2, NOx, O_3, PAN, F compounds, and others have led to the specification of objectives, standards or target loadings which, if not exceeded, can assure vegetation well-being. Such standards require much prior research on dose/response relationships, but once established permit the designing of rational pollutant - abatement strategies. Attention can then be directed to the most destructive of pollutants and thus, the degree of abatement has a scientific basis. The definition of objectives for gaseous pollutants has been difficult but despite these difficulties, the principle of defining objectives has been extended to include pollutants deposited in precipitation. Many aquatic scientists feel it is possible to select a wet deposition loading for acid sulphate that represents an upper limit for the continued well-being of lakes in sensitive areas. Indeed, the abatement strategy for SO_2 emissions currently being implemented in eastern Canada is based on a particular wet deposition loading value or environmental objectives (20 kg ha^{-1}. yr^{-1}). Clearly, the specification of environmental objectives applicable to terrestrial resources is of paramount importance and constitutes the ultimate aim of both dose/response and more detailed research.

4.2.2 **Which Environmental Objectives Should we be Concerned with?**

Three factors should be considered to determine environmental objectives. First, the nature and amount of pollutants in the atmosphere of various regions in Canada. Second, the extent to which such pollutants are known to be potentially injurious to terrestrial ecosystems by direct and indirect mechanisms. Third, the characteristics of receptor materials or organisms that determine resistance or sensitivity.

Long-term average SO_2 concentrations are very low in most regions and, except in a few instances around strong emission sources, well - established environmental objectives, expressed as ambient concentrations, are not exceeded. Although phytotoxic concentrations or environmental objectives have been elaborated for ozone, the networks are too skeletal to quantify the threat that is suspected in the Windsor to Quebec City corridor and in the Greater Vancouver area. With regard to mixtures of pollutants, the situation is worse for a similar but slightly wider geographical area, and no specific objectives for the mixtures have been developed. The situation is also very unsatisfactory for hydrocarbons because emissions are as large as SO_2, yet the spectrum of compounds present is largely unknown. Flourine emissions affect only

local areas and environmental objectives have been well-developed. Summarizing for gaseous pollutants, therefore, we have reasonably good environmental objectives for SO_2, O_3 and F, but not for CO_2, hydrocarbons or pollutant mixtures. For O_3 and hydrocarbons the weakness lies in the monitoring networks, especially in forested areas.

Environmental objectives for wet and dry deposition do not exist for terrestrial systems. For direct effects of acidic deposition, the same basic concept as that used for gaseous pollutants seems to apply in that, dose is a function of some combination of concentration and duration of exposure. For indirect effects, on the other hand, this is certainly not the case because pollutants are known to accumulate in the soil system.

4.2.3 Trends and Difficulties in Developing Environmental Objectives

The researches of Cox and Percy, reported elsewhere in this assessment, show very convincingly that simulated acid rain, similar in composition to that received in eastern Canada, can adversely affect plant growth processes. This research on the direct effects of wet deposition is laying the foundation towards the elaboration of new environmental objectives. From this, it is a less complex step to go from a minimum desirable pH value for precipitation and to translate this to acid sulfate and nitrate deposition values, and, in turn, to maximum permissible emission levels.

For effects on soils, the subject is more complex, and invalid extrapolations are sometimes made from short-term lysimetric experiments that do not resemble long-term natural processes. Contrary to what is sometimes alleged, there could be injury to neutral or calcareous soils through the continued deposition of potentially toxic elements, so there is a need, particularly in southern Canada to develop environmental objectives for metals. On the other hand, acid deposition may only marginally increase the normal leaching loss of bases from such soils, although a lysimetric experiment conducted using such a soil of pH 6 with simulated acid rain of pH 3.5 will inevitably show an accelerated loss of bases in the percolates. The acidity may remain the same because it is determined by intrinsic soil processes. The reactions are complex because a slow mineral-weathering process is taking place, which mostly overrides any effect of acid deposition. There is increasing realization that the reaction of acid forest soils with acidic deposition, especially acid sulfate, is very central to the development of environmental objectives designed for the forest. As the reactions of acid forest soils are also influenced by harvesting and other forest management practices the elucidation of this objective should be one of our highest priorities.

For acid nitrate deposition there are also unknowns. Nitrate deposition at Canadian levels may benefit the boreal forest, but it may also contribute to the spring flush of acidity, if not retained by forest humus. It is also difficult to define the role of NO_x since part of the NO_x emitted contributes to the formation of ozone which may or may not reach the Canadian boreal forest. There is much to discover therefore, before an environmental objective can be designed for NO_x taking into account forestry concerns.

4.3. EFFECTS ON VEGETATION

4.3.1 LABORATORY EVIDENCE

4.3.1.1. Physiology and Biochemistry

Acid deposition and O_3 are fundamentally different in the way in which they bring about injury to plants at biochemical and physiological levels. Ozone is a very reactive gas that can penetrate the open stomatal pores of the leaf, diffuse across the sub-stomatal cavity and interact with the internal tissue of the leaf. Acid deposition, on the other hand, is not free to penetrate the stomatal cavity, though some may, and so must exert its influence on the leaf surface. The differences in the physical nature of the pollutants determines the route of entry and subsequently the site of initial injury.

Initial Mode of Action-Ozone

Ozone, because of its reactive nature is generally thought to react with the first internal chemicals and structures with which it comes into contact. As ozone diffuses across the substomatal cavity, the first cellular components that are encountered are those associated with the cell wall. While cell wall carbohydrates are not easily altered by O_3, cell wall proteins (e.g. wall synthesizing enzymes) are. Studies by Ordin and Hall (1967) have shown that UDP-glucose polysaccharide synthetase is inhibited by O_3.

Interaction of O_3 with the plasmalemma and its effect upon cell permeability is of singular importance. Heath (1975, 1980) considers this to be the primary site of ozone attack on the leaf cell. Its interaction with the plasmalemma is largely determined by the high probability that it will encounter reactive substances or structure as it traverses the membrane. Since normal and specialized cell (e.g. guard cells) function is largely determined by changes in cell permeability, it is easily seen that alterations to the latter could result in profound changes in leaf function. A number of secondary effects are thought to occur following the breakdown of the cellular membrane but the primary effect is still considered to be related to water balance. Heath (1980) states that "most symptoms of air pollution can be attributed to the loss of water from the cell and the effects of altered water potential on cell metabolism". Through its effect on cell permeability and water relations O_3 obviously has the ability to modify or impair a number of physiological or biochemical processes associated with plant growth, reproduction and maintenance.

Mode of Action - Acid Rain

In 1977, Tamm and Cowling outlined some of the potential effects of acidic precipitation on vegetation. It was recognized that direct exposure of trees to acid deposition could result in; a) damage to protective surface structures, b) interference with the normal function of guard cells, c) poisoning of plant cells after diffusion of acid substances through stomata or cuticle, d) disturbance of normal metabolism or growth processes, e) alteration of leaf and root exudation processes, and f) accelerated leaching of substances from foliar organs. These hypothesized effects suggest that acid rain acts primarily through its interaction with the cuticular surface where acidification above a certain threshold leads to the collapse of the epidermal cells in that region. Some authors consider this to be the primary effect of acid rain (Heath 1980).

Evidence for the erosion of leaf cuticle in polluted environments is known from a number of studies in the field. Cuticular erosion related specifically to acid rain is thought to be injurious, but is only known from laboratory studies. This is largely because it is impossible to partition damage of this type to a particular agent in an environment where a number of pollutants are present. Thresholds for cuticular erosion are thought to be similar to those of visible injury and may even be related in a more direct sense (i.e. cuticular erosion leads to epidermal collapse thereby causing visible injury).

Physiological effects of acid rain in relation to guard cell functioning are not known and, in general, few studies have attempted to address the relationship between acid deposition and stomatal function, water loss, and carbon dioxide uptake, with one or two exceptions. Bidwell (1984) looked at the effects of simulated acid rain (SAR) down to pH 3.0 on the photosynthetic response of red pine, jack pine and red spruce. He found no significant effect of daily misting at these levels but observed trends that were "strongly suggestive" of acid rain impacts on photosynthesis, possibly through the loss of stomatal control.

What is the evidence that O_3 and acid precipitation can influence biochemical and physiological functioning?

Although the mechanisms by which O_3 inhibits metabolic functioning resulting in growth reduction or tissue death is well understood, the same cannot be said for acid precipitation. Several hypotheses for the mode of action of acid precipitation on physiological processes exist but a significant amount of research is required before a definitive statement can be made.

4.3.1.2. Plant Reproduction

The potential sensitivity of plant reproductive systems to air pollution rests on the exposure of the sensitive reproductive structures. Pollen development and activity are known to be among the more sensitive botanical indicators of atmospheric pollution (Stanley and Linskens 1974; Feder 1981). Atmospheric pollutants may directly affect vulnerable reproductive processes either by directly reducing pollen viability and pollen tube growth or by affecting the chemical environment of the stigmatic surface which may reduce stigma receptivity and change pollen stigma interactions.

Studies on conifers located at different distances from urban and industrial areas have shown marked reductions in cone dimensions, seed weight and viability together with reduced pollen viability (Antipov 1970). Furthermore, these effects may occur at pollution levels lower than required for noticeable foliar injury (Houston and Dochinger 1977).

Critical reviews by Cox (1983b) and more recently by Keller and Beda (1984) have shown inhibition of pollen function in at least 15 species by SO_2 fumigation including two Canadian trees (*Populus tremuloides* and *Pinus resinosa*). The pollen of 13 different Canadian forest species whose floral parts were exposed to wet deposition were significantly influenced by experimental applications of pHs from 5.6 to 2.6. The LD_{50} dosages of pH (the pH at which a 50% probability of death occurred) for all pollen tested were within the range of acidity found in acid rain events in eastern Canada (Cox 1983a). Acid deposition then must be considered a potential threat to pollen viability.

Interpopulation variation of pollen response to acidity and aluminum has also been investigated (Cox 1983b). This investigation showed that pollen of white pine sampled from a calcareous site was more sensitive to acidity than pollen taken from individuals on an adjacent acidic soil.

Few studies have examined the combined effects of trace elements and pH on pollen function. Responses of pollen from eleven Canadian forest flora species to combinations of pH with either copper, lead or zinc have been carried out by Cox (1985). Copper concentrations from 0.05 to 0.4 mg L^{-1} in the media were shown to influence pollen germination and tube growth. While significant inhibitions occurred in aspen and yellow birch pollen other pollen was stimulated, such as eastern hemlock, trillium and evening primrose. At current levels of regional deposition of this metal only the more sensitive species, sugar maple and yellow birch, may be affected. Copper however, significantly increases the sensitivity of pollen to pH. Similar investigations with lead or zinc demonstrated few effects on the individual pollens.

The effects of ozone on pollen function was first investigated by Feder (1968). Using tobacco pollen, as little as 0.1 uL L^{-1} O_3 for 5.5 h was sufficient to reduce germination and germ tube growth 40-50% both *in vitro* and on the stigmatic surface. 1.0 uL L^{-1} O_3 for more than 3 h completely prevented germination of the O_3 sensitive variety. Feder and Sullivan (1969) were able to correlate relative foliar sensitivity of the varieties of tobacco with pollen sensitivity and later Feder (1981) developed a bioassay for O_3 air quality using various tobacco pollens. Mumford *et al*. (1972) reduced corn pollen germination *in vitro* with .06 uL L^{-1} O_3 which also increased amino acid and peptide accumulation suggesting O_3 induces autolysis of structural glycoproteins and stimulates amino acid synthesis. Benoit *et al*. (1982b) was able to show significant inhibition of white pine pollen under wet conditions by 0.15 uL L^{-1} O_3 but was unable to correlate pollen and foliar sensitivities.

The above *in vitro* pollen sensitivity to air pollution, although a guide to the potential effects, must be shown to operate on the stigmatic surface in order to be of concern. The effects of simulated acid precipitation on stigmatic receptivity of *Oenothera parviflora* have been examined by Cox (1984) where simulated rains of 0.26 cm prior to controlled pollination demonstrated a significant ($P < 0.01$) 20% reduction of stigmatic receptivity by simulants of pH 3.6 and 2.6 as compared with the pH 5.6 control. Stigmatic receptivity of aspen also declined significantly with decrease in simulant pH. Studies by DuBay and Stucky (unpublished report) on agricultural crops indicated that simulated rains of pH 2.5 for 2 h caused failure of fruit set in cotton. At pH 3.5, there was a decrease in mean fibre and seed weight but this was not statistically significant. A similar study with wheat florets exposed after self-pollination to simulated rain of pH 2.5 for 3 h produced significantly fewer seeds ($P < 0.10$) than those treated with pH 5.5 rain. Another preliminary report by Craker and Herbert (1984) suggested that a single exposure of corn silks and tassels to simulated acid rain can reduce the number of filled kernels and size of ears.

One consequence of reduced pollen viability on the stigmatic surface brought about by the direct effects of air pollution is a reduction in the number of ovules fertilized and thus the number of seeds produced. Simulated acid precipitation effects on aspen reproduction (Cox 1985) indicated significant increases in fruit abortion with decreases in pH of simulant was related to decreases in *in vivo* pollen germination.

What is the evidence for acid rain and ozone effects on plant reproduction?

Acid rain at the pH seen in eastern Canada and ozone at levels of 0.1 uL L^{-1} have been shown to affect pollen viability in experiments. The increase in fruit abortion by aspen caused by simulated acid rain was related to reduced pollen viability on the stigmatic surface.

4.3.1.3. Visible Injury/Growth and Yield

4.3.1.3.1 Acid Rain Effect on Forests

Studies attempting to determine the effects of simulated acid rain on tree growth and development under "controlled" conditions have been carried out since the mid 1970's, often with confusing results. The general purpose of most of these experiments has been to investigate the relationships between simulated acid rain, symptomatology and tree sensitivity as measured by some morphological or physiological change. The greatest difficulty in the interpretation of the experimental evidence is that because of extreme variations in pH, anion ratio, deposition rate, recovery period and species, it is almost impossible to find a unifying thread that would lead us to a meaningful conclusion. In many cases the only similarity among the studies is that acidified aqueous solutions were sprayed onto plant surfaces under "controlled" conditions.

Visible injury is often measured in pollutant studies and is primarily sought as an index of dose or even impact. Ideally a specific symptom is produced that is quantifiable as a function of the level of pollutant that is present. This is seldom the case, but visible injury can serve as a reference point for rapid assessment of species, or cultivar, response to a given pollutant. In the case of simulated acid rain, visible injury is characterized in terms of the appearance of necrotic spots or lesions on the adaxial surface of the leaf. These lesions are often associated with stomata, trichomes or vascular areas and can lead to the conditions of hypertrophy and hyperplasia (Evans _et al_., 1978). Erosion of the leaf occurs in the abaxial direction as the lesion enlarges. This progression appears to be related to the continued presence of acid rain of low pH.

In yellow birch, injury often occurred in the newly expanded or expanding leaves with young seedlings being more susceptable than old (Wood and Bormann, 1974). Current limits to visible injury (e.g. necrotic spots, lesions) as determined from a number of experimental studies are shown in Table 1. The upper pH limit for injury for the species examined seems to be in the region of 3.0 for both conifers and deciduous species. There is a suggestion that conifers are slightly more resistant based on estimates of visible injury (Evans _et al_., 1978) but this has not been demonstrated conclusively.

Sensitivity or resistence appears to be influenced to some extent by the age of plant material, its cultivation history as well as morphological characteristics. Perhaps the greatest deficiency associated with estimates of visible sensitivity to simulated acid rain is that very

little of the work has been performed on field grown material. Current studies with crop plants (Linzon and Kuja, pers. comm.) are presently aimed at filling this void but silvicultural species have received less attention.

It would appear that visible injury to plants from acid rain is primarily related to the physical and chemical characteristics of the leaf cuticular surface. Studies by Evans et al. (1978) suggest that an abundance of trichomes, or a higher stomatal frequency are not significant factors. If the cuticle is wettable, simulated acid rain is better able to penetrate the cuticle and to initiate lesion development in the leaf epidermis. If this is the case, there should be a relationship between leaf epicuticular waxes and foliar injury. This appears to be an area where there is considerable research activity at the present time (Cape 1985, Huttunen 1985).

If we assume that variations in light intensity, temperature and water stress bring about differences in the quality and quantity of epicuticular waxes (Cape 1983), and, that foliar injury is a function of the nature and amount of epicuticular wax, then field grown material is likely to be more resistant to the effects of acid rain than is material grown in controlled environments. It is reasonable to assume therefore, that the pH levels of rain would have to be lower than 3.0 to produce visible symptoms on tree species in the natural environment. This level of acidity (pH 3.0) is seen to be at the upper range of levels of acidity currently experienced in the natural environment in Canada (Barrie and Sirois 1982).

What is the evidence that acid precipitation can affect the forest?

Simulated acid rain has been shown to cause visible injury to plants but only at pHs that are rarely seen in most forested areas. It appears that pH would have to be below 3.2 to produce visible symptoms on native tree species.

4.3.1.3.2 Ozone Effects on Forests

Ozone is the most prevalent phytotoxic air pollutant on a regional scale in eastern North America (Linzon, 1985). Ozone is not emitted directly by any stationary or mobile source but is formed in the atmosphere in a photochemical reaction involving precursor pollutants: nitrogen oxides and reactive hydrocarbons. The two precursor pollutants are emitted mainly by automobiles. Nitrogen oxides are also emitted by high temperature combustion processes and fossil fuel electric generating stations while hydrocarbons are also emitted by various petroleum operations.

Since it takes time for O_3 to be formed in the atmosphere, high concentrations are usually found downwind of the sources, with O_3 affecting agricultural crops or forests often hundreds of kilometers from the sources of the precursor pollutants.

Many reviews on the effects of O_3 on vegetation have been written which discuss dose-response relationships, the symptoms of injury, sensitivity of plant species, and the reduction in growth and yield of crops and trees (Hill et al., 1970; Linzon et al., 1975; and Jacobson, 1977). Trees listed as sensitive to O_3 include white ash, trembling aspen, catalpa, honey locust, silver maple, Eastern white pine, ponderosa pine and Virginia pine.

Nitrogen oxides are important in that by combining with other pollutants they can lead to the formation of acid rain and O_3, which are both long range transported pollutants. It is well documented that O_3 is responsible for widespread and costly damage to agricultural crops both in the United States (Heck et al., 1982a) and in Canada (Linzon et al., 1984). Ozone has caused extensive damage to forests in California (Miller et al., 1982), with significant reductions in radial growth increment having been measured in ponderosa pine and white fir forests (Ohmart and Williams, 1979).

Visible symptoms

Ozone damage to forests in eastern North America has been extensively investigated in the Blue Ridge Mountains of Virginia starting in the early 1970's (Skelly et al., 1983). Elevated concentrations of O_3 were measured frequently from April to October, and eastern white pine was the first tree species to exhibit symptoms of O_3 injury. Symptoms included reduced needle length and needle retention, foliar chlorosis, and reduced radial growth. Oxidant air pollutant induced symptoms were also seen on tulip poplar, green ash, hickory, black locust, table mountain pine, Virginia pine, pitch pine and hemlock. Open top chambers in which O_3 was filtered from air entering the chambers which enclosed several coniferous tree species resulted in an increased height growth of up to 26% compared with trees growing in the open. Ozone concentrations in the air were found to increase with elevation throughout the study region and foliar injury on sensitive tree species was greater at the highest elevations (Skelly et al., 1983).

Studies on needle blights of eastern white pine have been conducted in several locations in eastern North America starting in Canada in 1959 and in the USA in 1961 (Linzon and Costonis 1971). In fumigation experiments in North Carolina, Berry and Ripperton (1963) induced a tip necrosis on newly developing immature needles of eastern white pine with 0.065 uL L^{-1} O_3 for 4 h. Costonis and Sinclair (1969) in New York State showed that O_3 acting on the new needles of certain sensitive strains of eastern white pine could cause a wider range of symptoms from silvery and

chlorotic flecks through chlorotic mottling to tip necrosis. In artificial fumigation experiments this syndrome was induced by controlled doses of O_3 of 0.07 uL L^{-1} for 4 h or 0.03 uL L^{-1} for 48 h. At Chalk River, Ontario, in experimental fumigations Linzon (1973) induced chlorotic flecks on new needles of eastern white pine with concentrations of 0.10 uL L^{-1} O_3 for 6 h. In field studies at Chalk River, Linzon (1973) found chlorotic flecks developing on new needles of eastern white pine ramets (clonal grafts) which had been exposed to ambient air containing O_3 concentrations of 0.03 uL L^{-1} or over for periods of 10 to 15 h, while no fleck symptoms developed on ramets which had been covered with polyethylene bags.

A number of studies have been conducted on the effects of O_3 on various tree species under controlled conditions. Davis et al. (1981) artificially fumigated several tree species in Pennsylvania with 0.20 uL L^{-1} O_3 for 5 h periods and found black cherry to be the most sensitive species, exhibiting 27% foliar injury. In fact, visible injury was produced on black cherry foliage at 0.10 uL L^{-1} O_3 for 4 h and 0.19 uL L^{-1} O_3 for 2 h. Karnosky (1976) in New York State produced injury on foliage of trembling aspen in artificial fumigations with 0.05 uL L^{-1} O_3 for 3 h. Eighteen species of coniferous tree seedlings were exposed to 0.10 uL L^{-1} O_3 for 8 h or to 0.25 uL L^{-1} O_3 for 4 to 8 h in Pennsylvania by Davis and Wood (1972). The six most sensitive tree species in descending order of sensitivity were Virginia pine, jack pine, European larch, Austrian pine, Scots pine and eastern white pine. Chlorotic mottle and tip necrosis or complete needle necrosis were the most commonly observed symptoms.

Growth and Yield

Nine forest tree species were exposed to chronic O_3 fumigation (0.30 uL L^{-1} O_3 for 5 months) in Ohio by Jensen (1973). Significant reductions in growth were found in sugar maple, silver maple, and sycamore. Jensen and Dochinger (1974) in Ohio reported from 50 to 62% significant reductions in dry weight of new shoots of hybrid poplar cuttings exposed to 0.15 uL L^{-1} O_3 for 8 h/day, 5 days/wk, for 6 wks. Noland and Kozlowski (1979) fumigated silver maple seedlings with 0.30 uL L^{-1} O_3 for 6 h on each of 2 successive days in Wisconsin. The maple seedlings had been previously supplied with different concentrations of potassium in Hoagland solution for 6.5 weeks. About 26% injury was induced on the maple leaves which had been supplied either 0 or 2 mg L^{-1} K in nutrient solution, while 57% injury was induced on seedlings supplied 117 mg L^{-1} K. High K influences greater stomatal openings on leaves which resulted in greater O_3 uptake and greater injury by the pollutant.

Effects on growth and yield of tree species are usually associated with visible injury to the photosynthetically functional foliage. In fumigation experiments, Kress and Skelly (1982) in Virginia found significant growth reductions (height and total dry weight) for sugar maple, sweet gum, American sycamore, green ash, loblolly pine and pitch pine exposed to 0.10 and/or 0.15 uL L^{-1} ozone 6 h/day for 28 days. Foliar biomass of native ground vegetation was reduced by 30% in ambient air compared with filtered - air chambers without the occurrence of foliar symptoms of O_3 on most plant species (Skelly et al., 1982).

Radial growth studies on eastern white pine in the Blue Ridge Mountains indicated that ambient O_3 concentrations reduced the growth of sensitive individuals by 30 to 50 per cent annually during the period 1955 to 1978 (Benoit et al., 1982a). Mann et al. (1980) found similar results for eastern white pines in eastern Tennessee.

In Ontario foliar symptoms associated with O_3 injury to white ash and eastern white pine have been observed by Ontario Ministry of the Environment staff to occur throughout southern Ontario and occasionally in central Ontario (Linzon, 1985). The one advantage which is enjoyed by Ontario's forest industry is the fact that O_3 levels generally decrease in a south to north direction and thus are lowest in the areas where boreal forests predominate. For this reason forest yield losses due to ambient O_3 in northern Ontario would be considered to be low when compared to the yield losses which have been measured in the agricultural areas in southern Ontario.

Foliar symptoms of O_3 (stipling on the adaxial surface) have also been observed in the southeast areas of Quebec on sugar maple and balsam fir (Bernier and Robitaille pers. comm.). Ozone concentrations in this area are 80 to 150 nL L^{-1} but these measurements although rural were not in forested areas (Maltais and Archambault, 1985).

What is the evidence for Ozone effects on forests?

Ozone at concentrations found in Canada have been shown to produce visible symptoms and reductions in growth and yield on forest species. The geographical location of much of Canada's forests reduces the exposure to ozone and, hence, yield losses are low.

4.3.1.3.3. Acid Rain Effects on Crops

The direct impact of acidic precipitation on agricultural crops is not well understood. Visible injury symptoms have been observed only once on a field grown crop (garden beets) exposed to ambient acidic precipitation and additional treatments with simulated acidic rain (SAR)(Evans *et al*., 1982a).

Researchers agree that sensitivity of crops to direct injury or damage from wet acidic deposition depends on a combination of physical, mechanical, chemical and morphological characteristics of leaves in conjunction with the capacity of biochemical and physiological systems to buffer acids once they have penetrated the leaf (Jacobson, 1980). Foliar sensitivity to acidic rain is also related to the stage in the life cycle of a plant when exposure occurs (Jacobson *et al*., 1985). Older tissue can be more sensitive to acid stress resulting in premature senescence (Shriner, 1985).

The findings of several controlled greenhouse studies have been recorded in the literature (Evans 1984). In these studies, potted crop plants were subjected to simulated acidic rain treatments of varied acidity to determine injury symptomology and establish visible injury thresholds. Visible, foliar injury, caused by SAR, occurs as localized whitish, discoloured, circular lesions (usually necrotic, where cells have been destroyed by hydrogen ions) observed on adaxial leaf surfaces (Evans *et al*., 1977a; Evans and Curry, 1979; Irving, 1978; Rathier and Frink, 1984). Foliar injury develops on leaves wherever droplets are retained after a rain event such as leaf margins (Keever and Jacobson, 1983). Lesions are often associated with surface features, especially trichomes and stomata (Evans *et al*., 1977b).

With repeated exposure to highly acidic SAR (e.g. pH 3.0), lesions increase in size as more plant tissue in the vicinity of each lesion is affected. Eventually, leaves can become deformed or reduced in area, and their ability to photosynthesize may be inhibited. Erosion in leaf cuticles in response to simulated acidic rain, was described by Shriner (1978). Other responses have been observed such as premature leaf abscission (Ferenbaugh, 1976).

Microscopical observations of leaves of plants exposed to SAR have shown that incipient injury at the site of a lesion is characterized by collapsed epidermal cells (forming a pit) and damaged underlying palisade and spongy mesophyll cells. With repeated exposures, the mesophyll parenchyma cells display degradation of chloroplasts, degeneration of cell contents and finally, a collapse of cell walls. Palisade and spongy mesophyll cells can undergo hypertrophy (abnormal cell enlargement) and

hyperplasia (abnormal cell division) in tissue adjacent to lesions (Evans et al., 1977a; Evans, 1980; Tung, et al., 1982; Adams et al., 1984; Adams and Hutchinson, 1984. Reduction in chlorophyll in leaf tissue exposed to SAR was observed by Hindawi et al. (1980).

Evidence to date indicates that sensitivity of vegetation to injury from acidic rain is directly proportional to the wettability of foliage. Morphological features that contribute to increasing or decreasing surface retention of water by foliage can significantly alter the 'effective' acidic dose to which plant tissues are exposed (e.g. variations in cuticle thickness, presence of leaf hairs, and amount of surface waxes). Recent studies by Adams (1985) with cabbage showed that cotyledons were more severely injured at pH 3.0 than true leaves possibly due to the different nature of surface wax on leaves versus cotyledons affecting their relative wettability. Microscopic examination showed that water droplets on the leaves had large contact angles; however, droplets on the cotyledons had small contact angles indicating a more highly wettable surface.

Early studies have indicated that foliar leaching can occur in leaves exposed to SAR. Results of Wood and Bormann (1975) indicate that a significant increase in leaching of potassium, magnesium, and calcium from leaves of Pinto bean (Phaseolus vulgaris) occurs after exposure to SAR of pH 3.0 compared with controls (pH 5.0). Fairfax and Lepp (1975) showed a significant increase in foliar leaching of calcium in leaves of tobacco after exposure to pH 3.0 compared to pH 5.7. Loss of foliar nutrients may have a detrimental effect on plant productivity and ultimately crop yield.

Sensitivity to acidic precipitation may be related to the ability of a plant to neutralize acidic rain droplets on the leaf surface. Adams and Hutchinson (1984) showed that neutralization of acidic droplets was great in Artemisia tilesii plants, which also showed low sensitivity to foliar injury from SAR, whereas Spinach leaves were much less able to neutralize acid droplets and were also highly sensitive to foliar damage. They attributed this neutralization to cations leached from the leaves.

Various injury thresholds have been reported for a number of crops. Lee et al. (1980, 1981) subjected 35 crop cultivars (28 species) to SAR and observed that foliage of 31 was injured at pH 3.0. Carrot, cabbage, strawberry were not injured by SAR of pH 3.5. Foliar injury occurred in beet, swiss chard, soybean and green pepper at pH 4.0. Oats, wheat, barley and onion were not visibly injured by SAR with pH as low as 3.0. Generally, foliar injury was not related to effects on yield; however foliar injury of swiss chard, mustard greens and spinach was severe enough at pH 3.0 to adversely affect marketability. Crop groups were ranked in decreasing order of sensitivity to SAR; i.e., root crops > leaf crops > cole crops > tuber crops > legumes and fruit crops.

Greenhouse experiments were conducted at the Ontario Ministry of the Environment, Phytotoxicology laboratory in Brampton, Ontario to document injury symptomology of potted crop cultivars and other plants exposed to SAR in chambers (e.g. alfalfa, barley, cabbage, corn, cucumber, petunia, pinto bean, radish, soybean, tobacco, tomato). The tests showed that the crops vary in their sensitivity to rain acidity; however, visible injury almost always occurred on leaves, stems and flowers of all plants when treatment pH was 3.0 or lower (Enyedi and Kuja, 1985).

Although thresholds of foliar injury have been determined for several crops, it should be noted that inconclusive observations concerning the effects of SAR on plant productivity indicate that foliar injury is not a reliable diagnostic tool for predicting effects of increased rain acidity on crop yield (Shriner, 1985). Leaf injury estimates have been commonly used to assess pollution damage, but economic loss is not always closely related to leaf damage. Assessing loss based on visible damage may overestimate or underestimate economic loss (Irving, 1983).

Effects of SAR on plant growth and yield have been investigated in several controlled indoor experiments. Evans et al. (1982b) subjected greenhouse grown lettuce, radish, wheat, and alfalfa to SAR (pH 5.6, 4.6, 4.2, 3.4, 3.0, 2.6) under controlled conditions. Root yields (fresh mass) of radish were decreased 22, 42, 37, 41, 66, and 73% respectively compared to control plants. Similar reductions were present in radish shoot fresh mass. Yields of lettuce were reduced with increasing acidity; however, yields of wheat and alfalfa were not affected by SAR.

In a greenhouse study, Norby and Luxmoore (1983) determined that physiological processes in soybean were inhibited only from exposure to rain of pH 2.6. There was no evidence of adverse effects from SAR with pH 5.0, 4.2, and 3.4 on the physiology of the soybean cultivar. The authors concluded that vegetative growth of soybeans may be adversely affected by acid rain if pH is low enough (pH 2.6) to cause physical injury to leaves and loss of photosynthetic area.

Norby et al. (1985) exposed soybean to combinations of polluted air and SAR (pH 3.4, 4.2, 5.0). Growth was inhibited by SO_2 and O_3 but there was no evidence of adverse effects from acid rain on the physiology of this cultivar, regardless of gaseous pollutant treatment. In the absence of fundamental physiological disfunctions, the authors concluded that acid rain is unlikely to reduce yield.

In another study, greenhouse-grown radish plants were exposed to repeated applications of simulated acidic rain at pH values from 2.6 to 5.0 in order to determine whether growth and yield responses to acidic rain change with stage of development and whether plants have the capacity to recover from injury during rain free intervals (Jacobson et al., 1985). The results indicated that seedlings were more susceptible to repeated applications of SAR than older plants as indicated by foliar injury and

reduction in dry mass of roots and shoots. Exposures at an intermediate stage when plants were growing most rapidly caused the greatest reductions in root size. Also, rain free intervals between exposures to SAR allowed plants to recover from injury and compensate for growth reductions.

In a comprehensive review of experimental research concerning simulated acidic rain effects on crops, Irving (1983) concluded from experimental evidence that plant response to rain acidity varied considerably as a result of species and cultivar influences.

The effects of SAR on seed germination, seedling establishment and early stages of plant growth of 24 cultivars of six economically important agricultural crops (alfalfa, barley cabbage, corn, cucumber, soybean) were examined by the Ontario Ministry of Environment. For each crop, plants were exposed to a range of eight SAR treatments - pH 2.6, to 5.6 - applied in four indoor rain simulation chambers (Enyedi and Kuja, 1985). Findings of this study showed that test crops vary in response to increased rain acidity. Seedling establishment was not significantly affected by treatment with SAR. Shoot dry weight of cultivars was unaffected in 8 cultivars, reduced in 4 cultivars and stimulated in 12 cultivars. Root dry weight was unaffected in 8 cultivars and stimulated in 11 cultivars. It is suggested that an increased nitrate concentration in SAR treatments may stimulate the growth of some crops via a fertilizer effect. In most cases shoot and root response to simulated acidic rain were similar within individual cultivars.

The results of this study demonstrate that plant response to simulated acidic rain is not only species dependent but also strongly cultivar dependent. Thus, differential susceptibility is an important factor to be considered when interpreting results derived from 'effects' studies which utilize a single test species or cultivar.

What is the evidence for acid rain effects on crops?

Visible injury symptoms have been observed only once on a field grown crop exposed to ambient precipitation supplemented with simulated acidic rain. Simulated acid rain at pH of 3.0 or below has been shown to cause sufficient injury in several crops that economic losses are likely. Crop response to simulated acid rain is both species and cultivar dependent.

4.3.1.3.4 Ozone Effects on Crops

Although ozone injury was first observed and documented under field conditions in the Los Angeles area, the majority of research which followed through the 1950's-70's was conducted with pot-grown plants under greenhouse or controlled environment conditions. The advantages to this approach were good reproducibility under specific pollutant exposure and climatic regimes, exhaustive evaluation of dose (concentration-time) response functions, and, in some cases, detailed examination of the physiological and morphological mode/site of action.

Plant response to ozone is based on a sequence of biochemical and physiological events which terminate in some type of injury expression. The resulting cellular disturbances involve changes in both functional and structural characteristics resulting from disruption of cellular membranes. These disturbances can result in foliar pathologies, altered carbohydrate allocation, reduced growth and yield as well as impacts on plant communities and ecosystems (Guderian et al., 1985).

As with other air pollutants, ozone effects on plant foliage can be categorized into acute, chronic and subtle effects. Acute symptoms are characterized by bifacial lesions while chronic symptoms include pigmented lesions (stipple), bleaching and chlorosis. Subtle effects include reductions in plant performance or vigor without visible external symptoms.

On the basis of hundreds of ozone-plant response fumigations which have been conducted under laboratory conditions mainly in North America and Europe, exhaustive lists of crop sensitivity/resistance have been prepared and published (Guderian et al., 1985; Ormrod, 1978; Heck et al., 1977).

Many of the studies were conducted in controlled environment or greenhouse facilities in Canada using representative crop/cultivars, climatic conditions and dose regimes.

The development of dose-response models for use in establishing air quality criteria from studies conducted under greenhouse and environmental chamber conditions has been based primarily on the work of Jacobson (1977) who reviewed selected reports from controlled exposure studies to determine limiting values and in Canada by Linzon et al. (1975) who, in a similar manner, derived dose values for definite injury levels. Both approaches are believed to be suitable only for short-term acute effects causing visible foliar injury.

A comparison of the results from both approaches is shown in Table 2 below.

Based on these and other findings, Guderian et al. (1985) recently developed a set of maximum acceptable ozone concentrations which, if met, would guarantee reasonable protection of vegetation from short term acute exposures (Table 3).

Table 2: Comparison of Two Approaches for Establishing Dose-Response Relationships for Ozone Effects on Vegetation.

Exposure Duration h	Range in Limiting Values* for Agricultural Crops	Concentrations Causing 5% Injury** to Plant Foliage Sensitive	Intermediate	Resistant
	$nL\ L^{-1}$			
0.5	200 - 400	200	300	500
1.0	100 - 250	100	200	300
2.0	-	70	150	250
4.0	40 - 90	50	120	230
8.0	-	30	100	200

* from Jacobson (1977) - Values below which foliar injury would be unlikely to develop
** from Linzon et al. (1975)

Table 3: Proposed* Maximum Acceptable Ozone Concentrations for Protection of Vegetation

Exposure Duration h	Resistance Level Sensitive	Intermediate	Resistant
	$nL\ L^{-1}$		
0.5	150	250	500
1.0	75	180	250
2.0	60	130	200
4.0	50	100	180

* from Guderian et al. (1985)

The importance of these types of controlled ozone exposures has been overshadowed in recent years by the shift in research priorities to natural field exposure systems. However, in a recent summary of an APCA Speciality Conference which examined the entire U.S. effort in setting ozone standards Heck and Krupa (in Lee et al., 1986) commented on the significance of these types of studies and on the need for continued effort in this direction. With the recent Canadian research efforts on ozone flux density and its relationship with total dose and crop response (Amiro et al., 1984) perhaps better linkage between artificial and field exposure results will follow. This would greatly enhance the validity and impact of short and long term plant sensitivity thresholds such as those shown in Table 2 as they could be adjusted for specific environmental and meteorological parameters which might be expected under field conditions. Information from these types of controlled studies may also shed light on the unresolved issue of the importance of short term acute exposures which occur during seasonal exposures of crops under field conditions (LeFohn, 1984).

What is the evidence for ozone effects on crops?

Exhaustive lists of crop sensitivity to O_3 are available based upon hundreds of laboratory trials performed in North America and Europe. From these studies, Environmental Objectives for O_3 concentrations have been produced. Currently, field trials are attempting to test the validity of transferring laboratory derived objectives to field situations.

4.3.2. FIELD EVIDENCE

4.3.2.1 Forest Decline

The closest situation in eastern Canada to the forest declines occurring in Europe and eastern United States is the decline of sugar maple in Quebec and Ontario. Maple syrup producers in the eastern Townships of Quebec first expressed concern in the autumn of 1978. Scientists made visits to the area in 1980, 1981 and 1982 and observe that the decline increased in intensity each year (Gagnon et al., 1985a). The symptoms of damage include small leaves which tend to colour earlier than usual in the fall, loss of foliage from ends of branches, branch dieback, bark flaking off main branches and the trunk tap holes taking longer to heal, reduced rate of radial increment growth and tree death. In the summers of 1983 and 1984, 129 sample plots were established in Quebec on several different sugar maple ecological associations. Maple dieback was most severe in stands of maple, yellow birch and black ash (low wet areas with poor drainage) and in stands of maple, yellow birch and beech (mountain tops with thin soil and dry conditions). Thus sugar maple decline was most severe on the wettest (37%) or the driest sites (23%). Maple stands containing basswood as an associate were the most fertile and the severity of decline was usually less (12 and 17%). Soils were analyzed in the different sugar maple associations and the pH ranged from 4.0 to 4.7. A survey of four soils profiles which had been sampled in 1974 was repeated in 1984 at the Duchesnay experimental maple grove. All soils sampled in 1984 were found to have a lower exchangeable cation level (Ca, Mg and K) in both the surface and B horizons. In addition, the pH of the soil decreased in 1984 in three of the four profiles sampled. The authors suggested a number of hypotheses for the cause of the sugar maple decline, which included long-term factors such as harvesting accompanying tree species, tree age, tapping, livestock grazing, and air and soil pollution. Short-term factors included adverse weather and insect infestations. Secondary factors included *Armillaria mellea* root rot. Acid rain and air pollution were suggested as the most likely cause since the affected region receives the highest loadings of acid deposits, with the annual total being 40 kg of wet sulfate ha^{-1} yr^{-1}.

In Ontario, in the spring of 1984, a number of maple syrup producers from the Muskoka area complained to the Ministry of Agriculture and Food about the increase in dieback and mortality of sugar maple trees in the last six years. The producers felt that acidic precipitation may be involved and that continued sugar maple decline could jeopardize the local maple syrup industry.

A field study was designed by the Ontario Ministry of Environment to examine the etiology of the declining sugar maple trees. Questionnaires were given to each woodlot owner to provide a history of stand management. Permanent observation plots were established in seven woodlots in the Muskoka area of south-central Ontario and in one woodlot near Thunder Bay in northwestern Ontario. Soil from the woodlots, and foliage, twigs and roots from sugar maple trees exhibiting a gradient of decline symptoms were collected for chemical analysis. Increment cores were collected from sampled trees and discs were taken from felled trees to examine chronological growth patterns. In addition, atmospheric acidic deposition rates, forest management practices, site disturbances, tree age, site quality, the presence of diseases and the history of insect defoliation and weather records were investigated at each study site location (McLaughlin *et al*., 1985).

A summary of the 1984 study results indicates that the current outbreak of sugar maple decline in Muskoka first became evident about 1978. Based on both aerial and ground observations sugar maple decline symptoms were observed on trees throughout the Muskoka region, with no consistent pattern as to topography, aspect or site. When the data from the seven Muskoka study sites were combined, using the numerical decline index, 58% of the trees were considered healthy, 20% had light to moderate decline symptoms, and 22% exhibited severe maple decline. Although some degree of tree decline was observed on maples in all age classes it was most pronounced on older trees and on trees which had been tapped for maple syrup production or otherwise wounded. Site nutrient deficiencies were not implicated in the decline of sugar maple.

The soil at the Muskoka sites was acidic with a mean pH of 4.8 and contained high amounts of exchangeable aluminum, ranging from 6 mg to high of 40 mg kg^{-1} in mineral soil ($CaCl_2$ extracts). Declining trees in Muskoka suffered extensive root death and the fine roots had significantly higher aluminum concentrations than fine roots of healthy trees. The aluminum levels averaged 47% higher in fine roots from declining trees (4000 mg kg^{-1}) versus healthy trees (2730 mg kg^{-1}) which was statistically significant, ($p < 0.05$). A foliar chemical gradient was detected with reduced elemental concentrations in the tops of the tree crowns at Muskoka. Annual growth rings for both healthy and declining trees were very narrow during the two years of forest tent caterpillar defoliation in 1976 and 1977. Subsequent to the collapse of the insect epidemic, growth recovered in the healthy trees but not in the declining trees. Incremental growth in the declining tree population appeared to be falling relative to the healthy trees for 20 years prior to the caterpillar infestation suggesting that this group of trees may have been predisposed to decline perhaps by physiological, genetic or environmental factors. Early season droughts during the two years of the defoliation by insects (1976 and 1977) and again in 1983 and root infections by *Armillaria mellea* were some of the contributing factors to the tree decline.

The etiology of sugar maple decline is probably site specific, and may vary between individual trees and regions. At Muskoka the soils are acidic and are classified as sensitive; aluminum is freely available to trees and therefore the potential for indirect effects to trees exists. Higher amounts of aluminum were found in the fine roots of declining trees in Muskoka compared to healthy trees. Foliar tissue leaching and reductions in incremental growth on some trees may be environmentally related. Sugar maple decline is widespread throughout the Muskoka area and the region receives high loadings of acidic deposition (about 35 kg SO_4 in wet precipitation/ha/yr. These data suggest that acid precipitation, as an environmental stress, may be an additional factor to the complex maple decline syndrome.

From the above, it may be tentatively concluded from the first year's study of sugar maple decline at Muskoka, that the severe epidemic of forest tent caterpillar in the late 1970's combined with spring droughts in 1976, 1977 and 1983 were prime inciting factors. Armillaria mellea root rot, tree age and site management were contributing factors. Some data from the study suggested that acidic precipitation is an additional environmental stress in the Muskoka area.

What is the evidence for acid rain caused forest decline?

The complexity of environmental stresses in the forest system prevents attributing maple dieback in Quebec and Ontario to any specific variable but, acid rain has been implicated as a contributing factor in both provincial studies.

4.3.2.2. Forest Productivity and Dendrochronology

The influence of air pollution on tree growth is the primary concern of forestry. It has been estimated that, at current and future pollution levels, productivity reductions are likely (Fraser et al., 1985) and that these reductions may have major economic consequences (Forster and Crocker, 1985). Despite the concern, it has not been possible to attribute specific changes in forest productivity to air pollutants at this time. The difficulty is the number of factors that influence forest productivity such as climate, insects, diseases and management practices. In Canada, with only very few highly managed forests, and with such an immense forested area, many of the factors that are known to influence tree growth can only be inferred from general trends. This, then, provides the background against which any additional stress on the forest such as air pollution must be evaluated. In the case of regional air pollutants, the concentrations are, in the most part, not known precisely and are thought to influence forests in several subtle ways. The challenge of Dendrochronological studies on air pollution therefore, is to try to discern a relatively subtle effect against the very dramatic fluctuations that are caused by disease, insect pests and variations in climate.

Air pollution has been demonstrated to affect tree growth both in Canada and at numerous locations throughout the world. Many different pollutants have been implicated such as sulfur dioxide (Fox, 1980), ozone (Benoit et al., 1982a), fluorides (Carlson and Hammer, 1974), and heavy metals (Dendron Resource Surveys, 1985). In all of these cases, however, the effects have been seen around strong point sources of pollution where concentration or deposition gradients have been clearly described.

Regional pollution effects have been far more subtle and to date, there is still substantial controversy as to whether reductions seen in tree growth are related to pollutants either directly or indirectly. In Europe, air pollution has been implicated in growth reductions in Germany (Bauch, 1983), Switzerland (Schweingruber et al., 1983), Norway (Strand, 1983) and Finland (Huttunen, 1985) whereas in Sweden (Ministry of Agriculture 1982) comparisons between tree growth and air pollution were inconclusive. Recently, in the United States, there have been an increasing number of studies that have shown tree growth reductions in areas of high pollution loadings. Reductions are greatest at higher elevations and in softwood (coniferous) species (Johnson et al., 1981; Johnson and Siccama, 1983, and Bruck, 1985) but, growth of both low elevation softwoods (Hornbeck and Smith, 1985; McLaughlin et al., 1983) and hardwoods (Puckett, 1982; McClenahen and Dochinger, 1985) have been reduced in certain situations. These studies implicated air pollution to varying degrees but, in no case, was it possible to make a definitive statement as to the case of the reduction.

In Canada, the literature is much more restrictive. McLaughlin et al. (1985), in a survey of the Muskoka area of Ontario as part of a study on sugar maple decline, found that there was evidence of a reduction in the growth of certain trees up to 20 years prior to showing decline symptoms. The decline episode itself, however, appeared to be triggered by a severe defoliation by caterpillars. This study along with the observations that drought could also be the triggering mechanism for forest decline (Johnson and Siccama, 1984), emphasized the importance of the interaction between natural and anthropogenic factors.

In Quebec, maple decline is a major problem (Gagnon et al., 1985b) and attempts have been made to relate the problem to causal factors (Roy et al., 1985). Maple growth has decline 35% in the past 5 years as compared with the previous 10 to 20 years. Although air pollution could not be proved to be the cause, the investigators stated "We strongly suspect that the decline is caused by air pollution and acid deposition but we do not have the means to prove it." Other factors such as tapping, cutting of accompanying species, defoliation by insects and grazing by animals have been discounted.

The studies by both Ontario and Quebec are continuing and are attempting to determine the primary factors related to the decline of sugar maple in their respective provinces. In addition, Phase II of a survey by Dendron Resource Surveys Ltd. carried out under contract with the Canadian Forestry Service is examining the growth of both white and red spruce as well as sugar maple from south of Montreal to the Gaspé. In this area, regional pollution levels are largely known and are some of the highest in the country. Since the dendrochronological techniques used in this survey were evaluated in Phase I of the study (Dendron Resource Surveys, 1985), it is anticipated that this survey will permit an answer to the question of whether there are effects of regional air pollution on forest productivity in Canada.

What is the evidence for regional air pollution effects on forest productivity?

Regional-scale air pollution has been implicated as a contributing factor in the reduction of forest productivity both in Canada and elsewhere. Although pollutants have the potential for causing growth reductions as seen around strong pollutant point sources, there is still insufficient data to permit a definitive statement as to the influence of existing regional-scale pollution levels on the forests of Canada.

4.3.2.3. **Bioindicators**

Lower plants have frequently been used in the study of the deposition and effects of local pollutants (Richardson and Nieboer, 1981). Lichens and mosses are particularly good subjects for this type of research because of their simple tissue organization, their tendency to retain and accumulate ions, and their relative sensitivity to pollutants. These features also make them useful as biomonitors in the study of the long range transport of atmospheric pollutants (LRTAP) (Puckett, 1979).

Studies of the environmental impacts of short range transport of industrial and urban pollutants have provided basic information on lichen and moss toxicology and on mechanisms of metal uptake (Burton *et al*., 1981; Beckett and Brown, 1984). A variety of trace metals, including Cd, Cu, Co, Pb, Hg, Ni, and Ag are known to affect membrane integrity, photosynthesis and other aspects of lichen metabolism (Puckett, 1976; Burton *et al*., 1981). Vanadium at levels encountered in the field in the vicinity of oil sands recovery operations has been shown to significantly reduce phosphatase enzyme activity in several lichen species (LeSueur and Puckett, 1980). Enzyme activity is apparently not adversely affected by high concentrations of the metals Al and Ni, or by levels of nitrate, sulfate and acidity presently measured in the field in North America (Lane and Puckett, 1979).

Long range studies focusing on lichens and mosses have been of two basic kinds: firstly, inquiry into the direct and indirect effects of acid rain and trace metals on lichen and moss physiology and vigour; and, secondly, biomonitoring with lichens and mosses to detect and measure deposition of transported pollutants.

Studies designed to directly measure acid rain tolerance of lichens and mosses have shown that precipitation pH is a important factor in lichen and moss survival (Bailey and Larson, 1982). In the laboratory, wetting by simulated acidic rain caused a reduction in maximum photosynthetic capacity in the lichen *Cladina stellaris* and inhibited the rate of recovery from dormancy (Lechowicz, 1982). In two years of field studies on *Cladina stellaris*, lichen growth rates and cover were not affected by the pH of 3.5 and over (Lechowicz, 1983), although discolouration and some reduction of growth and cover were seen at lower pH. Varying relative concentrations of nitrate and sulfate in the precipitation in these studies showed no fertilization effects by nitrogen ions.

Hutchinson *et al*. (1985) have studied the effects of long and short term exposures to simulated acid precipitation in field plots of *Cladina* lichens and the moss *Pleurozium schreberi*. Lichens showed changes in morphology and reduced height and weight below pH 3.0, and reduced cover and lowered net photosynthetic rate below pH 3.5. There was temporary stimulation of growth at the low pH for *C. rangiferina* followed by

destruction of older tissues and eventual death. Growth and cover of Pleurozium were extremely sensitive to low rainfall pH. Below pH 3.5 nutrient status was altered and at pH 2.5 there was complete elimination of the moss carpet.

Biomonitoring with lower plants has been extensive. Tuominen and Jaakkola (1973) have published lists of metal levels typical of lichens inhabiting pristine areas of the world. Data on trace metal concentrations in a variety of species of lichen and mosses are also available for isolated locations in Canada. Tomassini et al. (1976) have published levels of Cu, Fe, Ni and S for 22 lichen species at 14 sites in the Mackenzie Valley, Northwest Territories. Groet (1976) provides data on the elemental content (Pb, Cu, Cd, Cr, Ni, Zn) of Hylocomium splendens and Pleurozium schreberi at remote Canadian locations, east of James Bay and in the Gaspé Peninsula. Gorham and Tilton (1978) reported data on mineral nutrient content of Dicranum polysetum and several species of Sphagnum in northern Saskatchewan. Pakarinen and Tolonen (1976) published data on the content of Ni, Cr, Fe, Cd, and Pb for Sphagnum fuscum from two rural sites in western Canada.

Deposition of airborne pollutants to mosses and lichens in rural areas of Canada has been measured and compared with levels in remote areas. Sulfur and lead were the only metals showing consistently higher levels in the lichen Cladina rangiferina in eastern Canada when compared with levels measured in the Northwest Territories (Zakshek et al., 1985a,b). With the exception of local anthropogenic or natural sources, concentrations of the metals Cr, Fe, Hg, Ni, Ti and V were the same as those found in the Northwest Territories. In the Maritime provinces of Canada, Percy (1983) determined patterns of atmospheric deposition for the elements Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, S, and Zn at 61 ombrotrophic bogs, using the moss Sphagnum magellanicum. The study showed no concentration gradients of a regional scale, but identified localized zones of enrichment, associated with local emissions. Zakshek et al. (1985a) compared levels of S and Pb in the lichen Cladina rangiferina at 85 ombrotrophic peat bogs in eastern Canada with levels measured in lakes sampled on an east-west axis. For sulfur deposition, both receptors showed highest values in central Ontario and Quebec, with distinct east-west gradients. Lead did not show a distinct east-west gradient, however, lowest concentrations were in Newfoundland and greatest concentrations were in southern Quebec and Ontario. In Ontario, Case (1985) measured metal levels in several species of moss and lichen and showed that the metallurgical industry is the principal factor contributing to the metal content of lower plants in Ontario.

What is the evidence that lower plants respond to Acid Rain?

Substantial evidence occurs in the literature that lichens and mosses are both very sensitive to air pollution and accumulate these pollutants. Field studies have shown that responses to pollutants occur both around strong point sources and in more remote areas.

4.3.2.4 Crop Response to Acid Rain

Field studies are a more realistic means of estimating actual effects of acidic rain on plant growth and crop yield because experimental plants can be grown under 'normal' environmental conditions where standard agricultural practices are utilized. In some studies, devices such as open topped chambers and mobile rain exclusion shelters have been used by researchers to minimize interferences from ambient gaseous pollutants and ambient precipitation in test plots.

Irving (1983) stated that field research demands considerable time and labour and thus, is expensive. A high degree of replication and a high number of treatment levels is required so that subtle treatment effects can be observed above the differences caused by environmental variability. Also, reliable dose-response predictions for yield versus rain acidity cannot be made without at least repeating studies for 2 or 3 years.

To date, several crop species have been studied under field conditions; i.e. alfalfa, barley, beet, broccoli, bush bean, cabbage, carrot, cauliflower, corn, fescue, green pea, kidney bean, lettuce, mustard green, oats, onion, orchardgrass, pinto bean, potato, radish, red clover, rye grass, snap bean, spinach, soybean, strawberry, swiss chard, timothy, tobacco, tomato, wheat (Evans et al., 1982a,b, 1983; Heagle et al., 1983; Cohen et al., 1981, 1982). Reduced yield resulting from exposure to SAR (pH 3.5 or lower) was observed only in some cultivars of radish, beet, broccoli, mustard green, pinto bean and 'Amsoy 71' soybean. Stimulation in yield was observed at pH 3.5 or lower in several crop cultivars such as: fescue, 'Beeson' and 'Williams' soybean, alfalfa, green pepper, kidney bean, lettuce, orchardgrass, strawberry, and tomato.

Evans et al. (1982a) found that in field grown radish ambient rain and additional inputs of SAR had no significant effects on root or shoot biomass. Root yields of garden beets exposed to ambient rainfall and SAR at pH levels 5.7, 4.0, 3.1, 2.7 were reduced when compared with ambient plots (86% at pH 2.7, 84% at pH 3.1, 70% at pH 4.0). Kidney beans however, were not affected by SAR treatments (Evans et al., 1982b).

Troiano et al. (1982) also exposed field grown radish plants to ambient rainfall and additional SAR inputs and no visible injury was observed. Root yield however, increased with increased acidity. SAR of increasing acidity altered the ratio of shoot/root dry weight. The ratio became smaller at lower pH indicating a greater partitioning of photosynthate to the roots.

Pell (1985) investigated the impact of SAR on the quality and quantity of a field grown potato crop. She found that plants treated with pH 2.8 SAR exhibited small reddish necrotic lesions but the yield of tubers harvested as determined by weight and number was not affected by SAR. Also, the quality of the tubers, defined by total solid and total sugar content harvested was not affected.

Several field studies conducted on soybean cultivars have shown contradictory results with positive, negative and no net effect on bean yield (Evans et al., 1980, 1981, 1983; Troiano et al., 1983; Irving and Miller, 1981; Heagle et al., 1983). SAR with pH 4.0, 3.4, 2.8 did not have a significant effect on dry biomass of seeds, pods, stalks or shoots of soybean cultivars 'Beeson' and 'Williams' (Troiano et al., 1983). Heagle et al. (1983) found that foliar injury was observed at pH 3.3 and 2.8 in the soybean 'Davis' but there were no significant treatment effects on seed yield or seed quality (oil). Irving and Miller (1981) showed no significant treatment effects observed in 'Wells' soybean yield down to pH of 3.1.

Evans et al. (1981) subjected 'Amsoy 71' soybean to SAR of pH 4.0, 3.1, 2.7 and 2.3 in addition to ambient rain and determined that yield was reduced by 2.6%, 6.5%, 11.4% and 8.5% respectively. Decreased yields were attributed to a decrease in the number of pods per plant since seed number per pod and mass per seed did not vary among the treatments. On a per plant basis, total seed protein decreased by 10 and 19% in plants exposed to SAR of pH 4.0 and 3.1 respectively.

Irving (1985) investigated the response of 'Amsoy 71' soybean to temporal variations in rainfall acidity. The results showed that yield was not reduced significantly by acidity of SAR (pH 5.6, 4.2, 3.7, 3.4) and that event to event variation in acidity of SAR did not affect yield.

Banwart (1985a) showed significant treatment effects on the yield of both 'Amsoy 71' and 'Williams' soybean exposed to SAR (pH 5.6, 4.6, 4.2, 3.8, 3.4, 3.0) for an entire growing season. A field experiment designed to screen 20 soybean cultivars for sensitivity to acidic rain, was conducted under exclusion canopies at the University of Illinois (Banwart, 1985b). The conclusions of the study were that visible injury to the soybean at early stages of growth were not correlated to harvested yields. While variability was higher than expected, the average yield for all 20 cultivars studied was approximately the same at pH 5.6 and 3.0.

In a recent study by Plocher et al. (1985) in which 10 crop cultivars (alfalfa, tall fescue, barley, wheat, potato, tomato, radish, corn) were exposed to SAR (pH 4.0, 3.5, 3.0), no significant treatment effects on yield were determined with one exception. Corn yield was reduced at pH 4.0 but not at pH 3.5 or 3.0 in the 1981 study but not during the 1982 study. The authors concluded from results of these tests combined with results of earlier studies that acidic rain is not a serious problem for crop production.

What is the evidence for crop damage by acid rain?

Generally, field experiments to investigate the effects of simulated acidic rain on crop yields have indicated that the occurrence of foliar injury on plants occurs at lower pH than observed in green- house grown plants which are not hardened off. Repeated occurrences of rainfall of very low pH (e.g. pH 3.0 or lower) during the growing season will increase the likelihood of visible injury to crop plants. However, field experiments to investigate the effects of SAR on crop yields have suggested that foliar injury does not have a significant effect on harvested yield in most crop cultivars so far investigated.

4.3.2.5. Crop Response to Ozone

In recent years it has been demonstrated that foliar responses of crops to natural or artificial exposure with ozone may not be entirely effective as direct surrogates for crop productivity. Yield losses have been documented in the absence of visible injury and vice-versa (Tingey and Reinert, 1975). For this reason the main focus of ozone research has, since the late 1970's, been directed towards a field oriented assessment of ozone effects on crop yield, quality and productivity.

Any assessment of yield or quality parameters under field conditions is complicated by the ubiquity of ozone exposure, the effect of meteorological variables on ozone distribution within crop canopies and the effect of numerous biotic and abiotic factors which can alter plant response.

Some of these difficulties have been partially overcome by recent progress which has been made in the refinement of field assessment techniques, including open top field chambers, open air fumigation systems and ambient air pollutant gradients.

The most comprehensive program that addresses the issue of seasonal ozone impact on crop yield is the National Crop Loss Assessment Network (NCLAN) in the U.S. The experimental design consists of open-top chambers which have been modified to add or exclude ozone to achieve predetermined 7 h per day ozone exposure regimes. This dose concept with ozone being added in constant amounts to the diurnally fluctuating natural background levels, was developed by Heagle et al. (1979) who described it as a biologically relevant dose.

In the first yield assessment from the NCLAN study (Heck et al., 1982b), yield reductions in 5 different crops were reported along with the associated seasonal 7 h mean ozone levels. Using a simple linear regression model predicted per cent yield reductions for seasonal means of 60 and 100 nL L^{-1} were then calculated for the various crops. Linzon et al. (1984), in an assessment of ozone impact on crops in Ontario, used this model to calculate yield reductions at average seasonal means of 50 and 40 nL L^{-1}, common to southern Ontario. The yield reductions in the 5 crops for 50 and 40 nL L^{-1} seasonal mean ozone levels ranged from 2.7 - 20.6% and 1.6 - 12.3%, respectively.

In more recent NCLAN assessments of yield losses (Heck et al., 1983, 1984a,b) a three parameter Weibull model was used to predict production losses to major U.S. crops from seasonal ozone mean concentrations of 40, 50 and 60 nL L^{-1}. In the latest report (Heck et al., 1984b), the results for 11 crops averaged 4.0%, 7.6%, and 10.1% for seasonal means of 40, 50 and 60 nL L^{-1}, respectively.

Through this study and others of similar design it has now become apparent that attainment of the U.S. hourly criterion of 120 nL L^{-1}, which, on the basis of U.S. data equates to a seasonal mean ozone level of about 60 nL L^{-1}, will result in a significant impact on crop productivity. The economic impact associated with current ozone levels in the U.S. also has received considerable attention and numerous regional and national predictive models have been developed. The general concensus from the various studies is that the net productivity increase that would accrue in the U.S. from a lowering of existing ozone levels to background concentrations would be in the 2-3 billion dollar range (Heck et al., 1982a; Heck et al., 1983; Adams et al., 1984). Estimated benefits from more moderate 10% and 25% reductions in U.S. rural ozone levels are calculated at \$669 million and \$1.71 billion, respectively (Adams et al., 1985).

In most areas of Canada the assessment of ozone effects on agricultural crops either has not been done or has only recently been initiated. Examples include New Brunswick where foliar injury has been confirmed in 1984 and 1985 on potato (Tims, 1984) in British Columbia where tobacco indicator plots have been established (1985) to biologically evaluate ambient ozone effects (Runeckles 1985 - pers. comm.) and in Quebec where three sensitive crops were evaluated at three ozone monitoring sites in 1985 (Nadon - pers. comm.). In contrast, extensive efforts have been undertaken in Ontario to assess the impact of ozone on sensitive crops through 1) annual crop injury assessment surveys (Pearson, 1983), 2) numerous research studies (Cole and Katz, 1966; Weaver and Jackson, 1968; Wukasch and Hofstra, 1977; Ormrod et al., 1980) and 3) the development of a dose-response relationship to depict the economic impact of transboundary ozone (Linzon et al., 1984). These studies, together with supporting evidence from those which were conducted in the U.S. under the experimental NCLAN program, reveal that the attainment of the Canadian hourly criterion of 82 nL L^{-1} would result in a seasonal mean of about 30 - 35 nL L^{-1}, virtually eliminating current crop productivity losses. The resulting benefit to Ontario farmers alone from the attainment of this criterion has been estimated at between \$15-23 million annually.

What is the evidence that O_3 affects crop yields?

Ozone has been shown to reduce yield of several crops although most areas of Canada have not been assessed. It is apparent that if the Canadian hourly criterion of 82 nL L^{-1} was adhered to, virtually all current crop productivity losses would be eliminated.

4.4. EFFECTS ON SOILS

4.4.1. LABORATORY STUDIES

From the outset, it must be emphasized that laboratory experiments do not directly address the question "What evidence is there that LRTAP (Acidic deposition and Ozone) is affecting the Canadian terrestrial environment?" Rather, they are usually cited as evidence of what could happen to soils and eventually whole ecosystems at some point in the future should depositions continue. Further, as with any laboratory experiment, there are advantages and disadvantages. The advantages of such experiments include (1) the possibility that processes can be accelerated and results accentuated through the use of a wider range of treatments or accelerated loading schedules, and (2) closer control over experimental conditions. Disadvantages include (1) the fact that the degree to which the total environment can be simulated within the confines of a laboratory is limited and (2) even when credible simulations are made of various environmental conditions (e.g. simulated wetting-drying cycles, freezing-thawing cycles), it is not altogether certain that soils *in vitro* would, because of time considerations alone, respond to increased or accelerated loadings in a manner similar to that of natural soils. These types of experiments however have yielded valuable insights into individual soil processes or sets of processes.

Acidification and base-leaching are normal processes in humid region soils. In general terms, the processes may be envisaged as follows: Hydrogen (H^+) ions, either from precipitation or generated within the ecosystem, displace, by mass action, "base" (i.e. alkali and alkaline earth - chiefly Ca^{++}, Mg^{++}, K^+, Na^+) and other cations from exchange sites on the surfaces of soil particles; displaced cations react with mobile anions, (in pristine environments, HCO_3^- and/or organic anions; in polluted environments SO_4^{2-} and NO_3^- in addition), achieve electro-neutrality, and are transported out of the soil with the percolating solution. Rate of loss is often governed by the availability of leaching counterions. Other reactions in which H^+ and SO_4^{2-} may participate include various weathering reactions, microbial reactions, and solubilization reactions.

While some early monolith-lysimeter or leaching-column experiments, employing very high loadings of acids, suggested free movement of H^+ through soils, many recent studies have demonstrated considerable buffering ability of natural soils to H^+. Morrison (1981, 1983) observed considerable consumption of H^+ by both Podsol and Brunisol soils and an increase of H^+ throughput occurred only after soil bases were substantially depleted. The results suggested that the greater part of the H^+ was consumed in base exchange. Similar results were reported for other coniferous and hardwood soils (Hay *et al*., 1985; Hern *et al*.,

1985). Hay *et al*. (1985) suggested that, in addition to cation exchange, H^+ buffering may also be a consequence of the solubilization of organic matter from the LFH horizons of the soils. Boutin and Robitaille (in press) have shown that in a podzol, H^+ neutralization in leached organic horizons was achieved by the solubilization of NH_4^+ as a result of ammonification, acid hydrolysis and cation exchange with Ca^{++}. In the spodic horizons, the solubilization of Al is the major neutralizing mechanism followed by Ca^{++} and NH_4^+. *In vitro* nitrification greatly increased the acidity of the soil. Other processes responsible for H^+ consumption include carbonate weathering (in circum-neutral to alkaline soils only), aluminum buffering, iron buffering and silicate weathering.

Several investigations involving column-lysimeters have demonstrated considerable initial resistance to SO_4^{2-} and, eventually to cation movement (Singh *et al*., 1980; Morrison, 1981, 1983, 1986; Hern *et al*., 1985; Rutherford *et al*., 1985; Dimma and Neary, unpubl.). This has been attributed to adsorption of excess SO_4^{2-} from the leaching solution onto Fe and Al sesquioxides, particularly in the illuviated horizons. This mechanism effectively removes SO_4^{2-} from the leaching solution (the SO_4^{2-} presumably displacing OH^- which reacts with excess H^+). With restricted SO_4^{2-} movement, the additional leaching associated with SO_4^{2-} is prevented. The degree of SO_4^{2-} removal is proportional to the ability of the soils to retain SO_4^{2-}. While SO_4^{2-} adsorption appears to be a major mechanism, other soil reactions may also immobilize SO_4^{2-}. Under extreme loadings in one study, not all SO_4^{2-} could be accounted for by adsorption reactions or in the percolates, and some reaction of SO_4^{2-} with other Al compounds was hypothesized (Morrison and Foster, *in press*). Once SO_4^{2-} adsorption capacity is saturated by whatever means, cations (chiefly bases) move freely with SO_4^{-2} (Singh *et al*., 1980; Morrison 1981, 1983, 1986; Rutherford *et al*., 1985). Cronan (1980) also demonstrated free movement of SO_4^{2-} through monoliths comprised principally of organic horizons. In balance, the evidence from lysimeter experiments suggests that leaching from shallow organic soils, or soils with low SO_4^{2-} adsorption capacity, is a greater potential problem than leaching from deep mineral soils with high SO_4^{2-} adsorption capacities.

Hutchinson (1980), Morrison (1981, 1983), Rutherford *et al*., (1985) and others, all in Canada and using lysimetric techniques, have demonstrated that bases are displaced by H^+ and transported by SO_4^{2-} and other anions when soils are incapable of adsorbing further SO_4^{2-}. Studies suggest that while SO_4^{2-} adsorption defines the time soils are able to resist, base loss itself is largely a function of reserves present (Foster and Morrison, *in press*). Some column studies (Morrison, *in press*; Morrison and Foster, *in press*) also suggest that under extreme conditions weathering of (principally) silicate minerals may occur as well.

Evidence from column-lysimeter studies suggests that Al is readily mobilized to high concentrations, though only when the pH of the leaching solution falls sufficiently (Morrison, in press). Rutherford et al. (1985) demonstrated for a hardwood soil from Ontario and a coniferous soil from Quebec, that leaching was restricted mainly to the upper horizons of the soil and that solubilized Al was redeposited further down the column. The complexity of the Al speciation and associated solubility has been described by Arp (1983) and Ouimet and Arp (1985).

Column-lysimeter experiments have shown the effects of acidification on the solubilization and transport of organic compounds. Hay et al. (1985) reported that acid treatment suppressed the quantities of total organic carbon, total carbohydrate and fulvic acid in the percolating solution. They also reported that increasing acidity favoured solubilization of ammonium- plus amino-nitrogen compounds. Total soil N per se did not appear to be affected but nitrification appeared to be suppressed (Hern et al., 1985). Other studies in the field on the influence of acidity (caused by SO_2) or the microbial activity and nitrogen transformation processes have been carried out (Mahendrappa and Salonius 1984; Salonius 1985). These studies have demonstrated that below pH 3.5 microbial activity is greatly reduced.

4.4.2 FIELD STUDIES

The main concern that arises from the continued deposition of air pollutants on forest soils is that their chemical, physical and biological properties will be changed, perhaps irreversibly, to yield markedly less productive sites. In extreme cases, soils may be contaminated beyond the threshold where plant growth is supported. There are numerous regional-scale studies in the Canadian boreal showing how forest growth is often limited by soil nutrient concentrations and, hence, a depletion of nutrients by air pollution would have serious socio-economic consequences.

Evidence for the actual occurrence of soil changes comes from three sources; first, extreme situations around strong point-sources of pollution; second, from the testing of simulated acid deposition on soils at stronger than normal concentrations; and third, temporal or spatial comparisons that involve a "control" and a situation where regional-scale pollution levels are operating. For the temporal comparison the "control" is the same site but at a former time whereas for spatial comparisons the "control" is some distance away and is assumed to have been ecologically similar.

For the first two situations there is a wealth of evidence of actual soil degradation (Morrison, 1984). Toxic metals have been deposited to the point that the growth is no longer possible, soils have been further acidified to the point that a variety of pH-dependent properties have also suffered, the leaching loss of soil nutrients have been accelerated, the mobilization of soil aluminum and other toxic elements have been increased, and both microbiological and mesofaunal populations have been changed to an extent that organisms essential for litter decomposition, nutrient-release and the maintenance of soil structure are eliminated.

Difficulties arise when firm evidence is sought for soil degradation in regional situations or when extrapolations are made to the regional situation from the experiences gained from strong-point situations or from more extreme simulations.

The reasons for this are that at the regional-scale pollution intensity, soil changes are protracted and difficult to separate from those caused by other factors, while base-exchange phenomena are complex and not well understood. Thus, Canadian podzolic and brunisolic soils have developed their acute acidity and other characteristics over the course of the past 10,000 years in cool northern climates through the powerful action of carbonic and organic acids. Additional dilute sulfuric and nitric acids, arising from air pollution, are not estimated to contribute more than an additional 8 to 25 per cent of proton loading (Rowell and Wild, 1985). This may marginally accelerate the weathering process (Bache, 1985), but for very acid soils whose cation-exchange sites are largely occupied by

aluminum there may be little further change in the proportion of cation displacement or in pH. In other words, aluminum - not bases - will be lost from the system. Indeed, the strong presence of silicate, compared with other anions in catchment-budget outputs, shows the breakdown or weathering of complex alumino-silicate minerals that is continually taking place (Edwards et al., 1985). These considerations have led to the claim that at present acid deposition loadings, mineral weathering of the surficial deposits at Hubbard Brook will permit a rate of release of nutrients well able to continue to sustain forest harvesting at reasonable intervals. A similarly comfortable view has been taken for very acid podzols derived from granites in northeast Scotland receiving precipitation at an average value of pH 4.6. Periods of 1100 to 12000 years are estimated to be required for the serious loss of bases (Edwards et al., 1985).

Over much shorter time-scales there is confirmation of these findings for acidic podzols in Ontario (Linzon, 1980) and in Sweden (Wiklander, 1980). Contrary evidence exists for the northern Appalachians (Johnson et al., 1985), for southwest Sweden (Hallbäcken and Tamm, 1985) and for less strongly acid soils in England (Crowther and Basu, 1931) and Ontario (Linzon, 1980). Some of these effects are precisely those expected on less acid soils and suggest that on such sites a variety of adverse pH-related soil properties will also be affected (Glass et al., 1980). Present evidence is conflicting therefore, but suggests that additional proton loading is more likely to degrade less acid forest soils than acutely acid podzols, although the latter could show increased mobilization of aluminum.

Complicating the issue of changing soil properties is the influence of forest management practices. Data from the Swedish National Forest Survey show a strong correlation between the acidity of forest humus and increasing stand age (Tveite, 1985), while forest harvesting, through its preferential removal of bases, constitutes an acid-generating operation (Hornung, 1985). Closely related to this has been the Central European concern with acid nitrate deposition, for on certain sites an imbalance in nutrition and deficiency in bases has been brought about (Rehfuess et al., 1983). Acid nitrate levels are much lower than in Canada but there are Canadian sites where nutrient deficiencies give rise to visual symptoms that may be intensified by acid deposition. The concern expressed at the outset is real and there is still much to learn about the interaction of acid deposition with acid forest soils.

What is the evidence for effects on soils?

Evidence to date indicates that acid deposition has the capability to enhance the leaching of base cations and the solubilization of Al. These changes in the soil chemistry have negative effects on soil biological processes that are responsible for the long-term maintenance of forest vigor. Regional studies in Canada however, have not been able to demonstrate that these effects are neither large nor extensive.

4.4.3 SENSITIVITY MAPPING

Prior to 1980 little information was available on the potential impacts of acidic deposition on terrestrial ecosystems. It was recognized that inherent properties of natural soil and geologic materials and resultant reactions would alter the ultimate fate of incoming acidic compounds from atmospheric processes.

A number of acid precipitation terrestrial sensitivity assessments have been undertaken since the Canada-US Memorandum of Intent (MOI) agreement on transboundary air pollution in 1980. Soil and geology sensitivity mapping was required to delineate the extent and distribution of potentially sensitive terrestrial systems to the effects of the atmospheric deposition of acidic compounds. Mapping, in addition to providing a base for future monitoring, also provides an opportunity to review existing soil and geology information in terms of evaluating characteristics useful for environmental degradation studies. In particular, it provides a means of delineating areas where high acidic inputs and high sensitivities correspond and, therefore, more intensive investigation is required.

Some attempt has been made to assign a sensitivity rating to soils based on soil order. For example Lucas and Cowell (1984) considered sandy, acidic podzols to be the most sensitive with respect to base cation leaching and, hence, forest productivity. Clay-rich luvisols, in contrast, are generally well buffered with respect to aquatic ecosystem sensitivity.

Originally, single discipline maps were produced. Wang and Coote (1981) addressed the "Sensitivity of Agricultural Soils to Acidic Precipitation in Eastern Canada" and Shilts _et al_. (1981) produced a map on the "Sensitivity of Bedrock to Acidic Precipitation: Modification by Glacial Processes". These maps were user specific and limited databases may have restricted their applicability. More recent work by Rencz _et al_. (1985) has shown that it is possible to integrate data from several disciplines to better estimate a region's overall sensitivity to acid rain. Clearly, a multidiscipline or holistic approach to mapping was needed in order to incorporate those ecosystem components which interact to provide buffering to aquatic and terrestrial systems.

The Lands Directorate of the Environmental Conservation Service was the lead agency in producing a terrestrial sensitivity map for the MOI, examining potential aquatic sensitivity and, incorporating bedrock, soil, vegetation, water and land use information for Eastern Canada. This map was entitled "The Potential of Soils and Geology to Reduce the Acidity of Incoming Acidic Deposition". Methodologies and criteria developed for Eastern Canada through the MOI exercise have been broadly accepted across Canada and sensitivity maps for most provinces have been produced by their respective agencies.

Soil and geologic information was recognized as the best indicator of the long term capacity of watersheds to buffer acidic deposition and as such, maps were developed for interpretation of sensitivity to aquatic regimes. It was noted in the MOI that sensitivity mapping had been carried out in the presence of great uncertainties about soil and geological response to acid inputs and an even larger number of uncertainties about relationships between soil and geology, acidification and plant growth, or drainage water composition. The rating of the potential to reduce acidity (depending on terrain conditions) was based primarily on bedrock characteristics, on a combination of bedrock and soil characteristics, or primarily on soil characteristics. The rating system developed depended on the assumption that percolating water contacted soil, surficial geologic materials and bedrock in its passage to surface water systems and each component was rated accordingly.

Further efforts, such as in Western Canada, have resulted in mapping of "Soil Sensitivities to Acidic Inputs". Here it is recognized that glacial history, and surficial deposits as well as reactions in soils themselves, have largely masked the influences of bedrock on soil sensitivity. An attempt was made to relate sensitivity to productivity of agricultural, forest and natural vegetation systems. Three internal soil processes were accepted to be of highest significance: soil acidification and pH reductions; base cation loss; and aluminum solubilization. Individual sensitivities to these soil characteristics were combined into a single interpretation for sensitivity to changes significant to vegetation productivity.

Mapping the "Potential of Soils and Bedrock to Reduce the Acidity of Incoming Acid Deposition" with respect to receptor aquatic systems has been the principal approach taken in Eastern Canada because the effects of acidic precipitation on forest productivity and soil processes are poorly defined. This method is based on an aquatic sensitivity model developed by Lucas and Cowell (1984). The greater the potential of soils and bedrock to reduce the acidity, the higher its buffering capacity and the lower its sensitivity to acidic precipitation. Sensitivity criteria have included soil chemistry (exchangeable bases from Wang and Coote (1981), pH, texture, CEC, sulfate adsorption capacity), soil depth, drainage, landform relief, vegetation, vegetation cover, parent material and bedrock type.

In 1983, a series of three sensitivity maps of Eastern Canada were completed for the MOI. Since that time, provincial maps for Ontario, Quebec, Nova Scotia and Labrador have been initiated. Slight modifications to the original MOI mapping methodology have been made to accommodate regional differences in databases within each province.

Two maps are being developed in each of the four western provinces, Northwest Territories and Yukon under the guidelines established by the Task Group on Soils and Geology Sensitivity Mapping for the Western Canada LRTAP Technical Committee. Criteria and methodologies were initially based on those employed in Eastern Canada (Bangay and Riordan, 1983; Cowell et al., 1981; Lucas and Cowell 1984; Shilts et al., 1981; Wiens 1983).

To reflect impacts to aquatic systems the map "Potential of Soils and Geology to Reduce the Effects of Acidic Deposition" was accepted in a compatible context with Eastern Canada. The second map, "Soil Sensitivity to Acidic Inputs" was developed to reflect impacts for natural vegetation.

SUMMARY

Areas of potential sensitivity to acidic deposition have been delineated for most of Canada based on a common set of key mapping criteria. The revealed high sensitivity areas assist in the locating of monitoring plots and provide locations where intensive terrestrial-aquatic ecosystem interactions can be most effectively studied.

4.5. EFFECTS ON BIOGEOCHEMICAL CYCLES

In a natural forest ecosystem the cycle of elements between soil and vegetation maintains the chemical composition of the soil solution in a favorable state for meeting the nutrient requirements of a productive forest. The basics of a bioelement cycle are: input to the ecosystem from the atmosphere and mineral weathering; uptake from soil by trees and other vegetation; and transfer from trees to soil by a variety of processes including litterfall, canopy leaching by precipitation, root slough, and output from the tree rooting zone associated mainly with soil leaching. Ecosystem nutrient reserves are enhanced when atmospheric inputs are incorporated into the cycle and outputs from the tree rooting zone are minimized. The study of the circulation of nutrients in forest ecosystems therefore, becomes essential in the stress analysis of these ecosystems.

In the past decade there has been an increasing awareness of the magnitude of strong acid deposition in the northern hemisphere. Along with this awareness, there is concern that acid deposition may alter nutrient cycles in such a way that soil and soil water may become more acid and, therefore, less favorable for forest growth. For example, an increase in the acidity of soil water could reduce the availability of nitrogen (N), phosphorus (P), and base cations (potassium [K], calcium [Ca], magnesium [Mg], and sodium [Na]) and could increase the solubility of trace metals such as manganese (Mn) and aluminum (Al).

These possibilities and others can be examined using biochemical data from LRTAP and APIOS studies in eastern Canada. In particular, a comparison of nutrient cycling in (i) contrasting forest ecosystems within a single deposition zone and (ii) similar vegetation across a range of deposition are possible.

Mahendrappa (1983) compared precipitation and throughfall chemistries in three hardwood and six conifer stands within a radius of 5 km. He found that the percent of H^+ in precipitation (pH 4.2 to 4.5) neutralized by contact with a forest canopy may be as low as 20% in some species or as high as 80% in others. In general hardwoods had a greater capacity to reduce the acidity of rainwater than softwoods. Neutralization of acidity in precipitation by a maple-birch canopy at Turkey Lakes Watershed (Foster 1985a) exceeded the 18% by a balsam fir canopy at Lac Laflamme (Robitaille, pers. comm.).

Gizyn _et al_. (1985) reported that H^+ and SO_4^{2-} concentrations in throughfall and stemflow under white pine forest followed deposition gradients in incident precipitation concentrations but base cation concentrations did not. They suggested that the base cation composition of throughfall and stemflow were associated with nutrient cycling and soil derived availability rather than atmospheric deposition. Foster

(1985a) reported that exchange with H^+ ions may account for only 25% of the total base cation enrichment of throughfall in a tolerant hardwood forest. Acid precipitation, therefore, accelerates the rate of base leaching from the forest canopy.

The quality of water percolating through the soil is highly dependent on the physical and chemical properties of the soil. Differential flow patterns may exist in soil, depending on the network of macropores and channels created by root and animal activity. Water transported through macropores has less time to react and equilibrate with soil minerals than does slower moving capillary water. The soil properties having the greatest influence on acid precipitation chemistry are pH, CEC, base saturation and Fe hydrous-oxide content. These properties control the cation exchange buffering in soil as well as the leaching of displaced base cations.

Atmospheric H^+ inputs to the forest do not necessarily cause equivalent amounts of cation leaching from the soil if associated NO_3^- and SO_4^{2-} are immobilized. Nitrate losses from soil are strongly regulated by both microbial transformations and vegetation uptake. The highest H^+, Al and Ca^{2+} concentrations in a humo-fearic podzol supporting balsam fir were associated with the highest NO_3- concentrations (Robitaille pers. comm.). Nitrate may be released by forest ecosystems and pass into aquatic ecosystems (English et al., 1985) when the uptake of NO_3- is inhibited or when N retention capacity of the vegetation is exceeded. Sulfate losses are controlled by these processes and by SO_4^{2-} adsorption by the soil. Increases in SO_4^{2-} adsorption by soils are associated with increases in soil Fe hydrous-oxide contents. For example Lozano and Gizyn (1985) reported that differences between SO_4^{2-} concentrations in two podzolic soils in central Ontario were consistent with Fe oxide content of the soil and SO_4^{2-} adsorption. Hern et al. (1985) have proposed that SO_4^{2-} inputs to soil are immobilized by microbiological processes in the Turkey Lakes soil. Lysimeter budgets for SO_4^{2-} in the same soil (Foster et al., 1985) however, do not support the contention that SO_4^{2-} is accumulating in the most microbially active L-H horizons. Questions raised about the relative importance of microbial versus chemical immobilization of SO_4^{2-} need to be resolved.

Ion fluxes through a tolerant hardwood forest at Turkey Lakes Watershed have been estimated from observations of water and nutrient movement through the canopy, forest floor and mineral soil. Significant positive correlation in soil solution between Ca^{2+} and NO_3-, Mg^{2+} and NO_3- during the dormant period and between Ca^{2+} and SO_4^{2-}, Mg^{2+} and SO_4^{2-} during the growing season has been observed (Foster, 1985a). Sulfate concentrations alone were equal to 50% of concentrations of base cations in soil solution on an equivalent weight basis (Foster, 1985b). The flux of SO_4^{2-} beyond the rooting zone was roughly in balance with inputs to

the mineral soil which suggests either a lack of adsorption of SO_4^{2-} by the soil or that adsorption is in balance with mineralization of SO_4^{2-} in the mineral horizons. These studies and supporting laboratory experiments have demonstrated that SO_4^{2-} and NO_3^- are mobile anions in the Turkey Lakes soil.

Bulk precipitation collected at Turkey Lakes in 1982 contained 25.5 kg of SO_4^{2-}, 20.4 kg of NO_3^- and 0.5 kg of H^+ per hectare (Foster and Nicolson, 1984). Nichols and Verry (1985) have calculated emission related wet SO_4^{2-} deposition for the upper Great Lakes region, based on the relationship of H^+ to SO_4^{2-} in precipitation. The Turkey Lakes Watershed falls within the deposition zone of 12 kg ha^{-1} yr^{-1} of SO_4^{2-}. In a worst case situation, assuming no interaction of SO_4^{2-} with vegetation or soil, all this SO_4^{2-} might contribute to cation leaching from soil. The 12 kg of SO_4^{2-} could leach 240 Keq ha^{-1} of base cations from the soil in the worst case scenario, which would represent 15% of the current estimated base leaching (Foster unpublished). An additional 10% of the current base leaching would be related to anthropogenic NO_3^-, if we assume that the ratio of anthropogenic NO_3^- to natural NO_3^- in precipitation is similar to the SO_4^{2-} ratio and no removal of anthropogenic NO_3^- by vegetation or soil occurs. Mineralization of NO_3^- in soil and to a lesser extent, SO_4^{2-} make significant contributions also to the leaching of base cations below the rooting zone. Anthropogenic SO_4^{2-} would represent 27% of the total SO_4^{2-} leached from the soil (Foster unpublished). Base cations are being leached from the soil, therefore, in association with both anthropogenic and naturally derived SO_4^{2-} and NO_3^-.

In many eastern Canadian podzolic soils, the supply of exchangeable bases is often considerably less than in the Turkey Lakes soil; a factor that reduces the risk of further depletion of base cations by acid precipitation. In very strongly acid soils the cation exchange capacity is dominated by H^+ or Al or both. The question of the action of nitrate and sulfate inputs on soils and the subsequent effect on soil solution chemistry, as related to plant nutrition, is still in strong debate. Scientists are presently examining in more detail the role of nitrate in relation to positive or negative vegetation responses. Recent studies confirm that nitrate may be released by forest ecosystems and pass to aquatic systems (Cadle et al., 1985; English et al., 1985) or conversely may be retained by them (Papineau, 1983). Nitrate as a mobile anion leaches cations and is involved in the solubilization of basic aluminum sulfate (Driscoll, 1985) resulting in acidification. Also, when the retention capacity of nitrogen by conifers is exceeded leaching by mobile nitrate results thus causing a stress on the forest ecosystem. In some deciduous ecosystems SO_4^{2-} is the mobile anion (Foster et al., 1985).

A multiway description of groups technique has been utilized to examine the relationships among various soil solution cations and anions for various ionic gradients (Robitaille unpublished results). The data matrix was composed of over 1200 soil solution extractions for a four year period. The soil solution was extracted from a humo ferric podzol soil supporting balsam fir.

The analysis of H^+, Ca^{2+} and Al^{3+} in relation to NO_3^- and SO_4^{2-} indicated that NO_3^-, as opposed to SO_4^{2-} controlled the distribution of cations. It was apparent that the observed increase in soil solution acidity was dependent on an observed increase in NO_3^- at all levels of SO_4^{2-} Calcium had a tendency to increase with increasing NO_3^- at all levels of SO_4^{2-} except for SO_4^{2-} values higher than 146 ueg L^{-1} where it decreased. For a given level of NO_3^- the concentration of Ca^{2+} decreased for an increase in SO_4^{2-} for all levels of NO_3^-. Finally the highest H^+, and Al^{3+} concentrations were observed at the highest NO_3^- and the lowest SO_4^{2-} concentrations respectively. Overall, it may be said that H^+, Ca^{2+} and Al^{3+} increase and decrease respectively with increasing NO_3^- and SO_4^{2-}. This was confirmed by an analysis of the distribution of the molar ratio of NO_3/SO_4 which was 14 times higher for high levels of Ca^{2+} and Al^{3+} as compared with the lowest levels of these cations.

These observations affirm that NO^-_3 plays an important role in the Al^{3+}/Ca^{2+} soil solution chemistry of the humo ferric podzol supporting balsam fir.

Aluminum ions are likely to make a significant contribution to total cation concentrations in soil solution. According to Rutherford et al. (1985), increasing the acidity of soil solution in podzolic soils by addition of simulated acid rain (pH 2.0) resulted in increased Al mobilization and increased redeposition lower in the profile, so that actual Al leaching from the soil was very modest.

What is the evidence that acid precipitation is affecting nutrient cycling?

Acid deposition has increased the cycling of nutrients in some of the forest ecosystems that have been examined in eastern Canada. In particular, accelerated leaching of foliar and soil base cations have been reported. The chemistry of water within the forest ecosystem, however, is still largely controlled by the cycle of nutrients between the vegetation and soil. The effect of the increased cycling on nutrient uptake by forests is unknown.

4.6. THE EFFECTS OF ACID RAIN ON WILDLIFE

Current evidence of the impacts of long range air pollution on wildlife comes primarily from aquatic habitat changes specifically relating to the influence on food organisms such as fish and sensitive macroinvertebrates. Although the loss of an aquatic food supply is critical for wildlife species that utilize that resource (DesGranges, 1985), there also appears to be subtle effects of acidification that influence tissue element concentrations and reproduction in birds (Glooschenko et al., 1985). The precise mechanism by which reproduction is affected is still not well understood (Carrière et al., 1985).

Earlier investigations of the response of lichens and wildlife forage plants to sulfate exposure have been inconclusive, however, more recent studies (Case, 1985; Puckett, 1985; Zakshek et al., 1985a,b) have shown that the content of specific elements in lichens are significantly higher in eastern Canada than in remote areas. Through laboratory studies and the use of models, there are indications that an increase in deposition may very well influence the chemistry of wildlife tissues in the terrestrial system (Grodzinski and Yorks, 1981; Froslie, 1984; Beyer et al., 1985) as it does in the aquatic system (Kucera, 1983; Wren and Fischer, 1985). These are well enough developed that certain animals may be used as bioindicators in specific cases (Newman, 1979; Newman and Schreiber, 1984).

Not addressed in studies to date are the combined effects of long range air pollution and localized emissions on wildlife in North America. European studies have indicated both a reduction in growth and metal contamination in wild herbivores due to the combined sources of air pollution. (Jopp, 1979; Gydesson et al., 1981).

4.7. CURRENT HYPOTHESES ON FOREST DECLINE

4.7.1. HYPOTHESES FOR WHAT?

Before presenting and discussing hypotheses we should be clear as to what phenomena they relate. At the outset we may recognize two types of situations; First, those where there has been an unexpected change in forest growth or health, or an unexpected change in soil properties and, secondly, situations where there have been recorded no such changes of a discernible nature. This latter situation is included and is important because it embraces most of our current experience in the Boreal and Mixedwood Forests of Canada.

Within the first category there are three levels of change. First, the unpolluted or slightly polluted situation where growth declines have occurred; secondly, the strong point-source of emission situation where growth impairment has been dramatic; and thirdly the widespread regional situation where air pollutants are present and where some change in forest or soil has occurred. Hypotheses can only rationally be discussed if tied to these specific situations.

4.7.2 SPECIFIC SITUATIONS AND THEIR HYPOTHESES

Taking the first situation of an unpolluted or slightly polluted forest, where there has been a decline in growth or soil impoverishment, several explanations or hypotheses may be offered. These include climatic events, pathogens, insect epidemics, nutritional problems, site problems including waterlogging, and forest-management practices. In an unmanaged natural forest, the decline and death of individual trees through competition is part of the normal healthy scene. It has to be emphasized, too, that all these stresses may operate in the polluted forest and that often because of the lack of specificity in symptoms, the attribution of causes is hazardous.

For strong point-source of emission situations, the surrounding forest or soil usually contains excessive quantities of the pollutant causing dramatic effects or characteristic foliar symptoms. Sometimes airborne emissions damage and kill trees, without the soil being contaminated, but sometimes the soil becomes so contaminated that tree growth cannot restore itself, even after airborne emissions are reduced. There is usually no difficulty in pinpointing the cause. The third type of situation - of widespread regional malaise - is exemplified by Central Europe or parts of the United States Appalachians where diebacks or declines have become more widespread in recent years. One explanation pointed to "acid rain" as the culprit, with the warning that this would happen to Canada. The rapid rise in the incidence of dieback in commercial West German forests and the reporting of growth declines in Appalachian and Piedmont forests have combined to generate an upsurge of concern and research in both countries, with an emphasis on determining the cause of the problem and of implementing a solution.

It is this type of situation - one of widespread and unexplained forest decline - that is mostly in people's minds and for which explanations are sought. It is very difficult to say whether a similar situation is likely in Canada, but the occurrence of hardwood diebacks in eastern Canada in the 1930-50s, the present situation with sugar maple in Ontario and Quebec, and the importance of forests to the Canadian economy, all necessitate a thorough examination of the forest dieback phenomenon in Europe.

There are situations in Central Europe where forest injury has occurred over many decades and where the cause is high ambient concentrations of SO_2. This appears to be the situation in north-eastern Bavaria, where SO_2 concentrations average 8-27 nL L^{-1} and foliar sulfur concentrations are as high as 1.5-2.5 mg g^{-1}, as well as in Czechoslovakia and in other localities (Rehfuess, 1985). There are other situations - the Black Forest and southern Bavaria for example - where SO_2 concentrations

average only 8 nL L^{-1}, with short-term peaks of .19 uL L^{-1} (Krause et al., 1985), values which for the long-term are below IUFRO standards (IUFRO, 1983). The same is true for the rural NOx concentrations which at less than 8 nL L^{-1} are far below the .02-.03 uL L^{-1} level for phytotoxicity (Krause et al., 1985).

There has also been a recurring dieback problem with silver fir going back over 200 years. From about 1980 onwards dieback problems were experienced with higher elevation Norway spruce, and this has caused considerable concern. Spruce is a much more important commercial species, the trouble was recorded in what were regarded as "clean" areas, and since 1980 the incidence of trouble has intensified, spreading to other species, soils, elevations and Central European localities.

For some years the main hypothesis heard in North America to explain this phenomenon was that attributed to B. Ulrich and his school (Ulrich et al., 1980; Matzner, 1985) working in the very acid loess soils of the Solling plateau. Their hypothesis - called the "indirect pathway" - is that there is a cycle of warm, dry summers separated by cool, moist ones. During the former, protein compounds in the soil organic horizons are nitrified, the additional nitrate intensifying acidification and solubilizing more available soil aluminum. During the cool, moist summers protein builds up again, the acidity lessens and aluminum goes out of solution. For the acid loess soils of the Solling there is always some aluminum in solution. The effect of the additional acid sulfate and acid nitrate deposition (from air pollution) on this system is to intensify acidification and to raise soil aluminum levels and aluminum/calcium ratios so much in warm dry summers as to cause extensive rootlet mortality (Hutterman and Ulrich, 1984). The trees become so weakened that rootlet regrowth cannot occur and pathogens invade. The difficulty with the Ulrich hypothesis is not that it may not be reasonable for the poorly drained, plateau soils of the Solling, but that it appears less plausible for the well-drained till and less acid soils elsewhere in Central Europe where similar symptoms of dieback are reported. There is, nevertheless, the difficulty of the rapid escalation of dieback since 1980 over a period when acid sulfate deposition has been declining.

In 1983 North Americans heard firsthand from Peter Schütt outlines of other hypotheses. Schütt's own theory (1983) envisages a more embracing impingement or "general stress" through air pollution, made up of ambient concentrations of pollutants, acidic deposition, the contribution of nutrient, growth-altering or toxic substances which collectively lead to a decrease in net photosynthesis and to a general debilitation in a tree's vigour. This results in the tree being less resistant to other stresses, including drought, nutrient deficiency, insects and pathogens. The Schütt hypothesis might be viewed as embracing both direct atmospheric and indirect soil factors, but because none is quantified the significance of a particular atmospheric component is difficult to assess.

The second main specifically soil hypothesis envisages a nutritional imbalance brought on by excess nitrate deposition (Zoettl, 1985; Rehfuess, 1985). For many sites calcium and particularly magnesium supplies are marginal and the excess nitrate causes calcium and magnesium levels in tree tissues to fall below levels for adequacy. In the case of magnesium, chlorophyll formation cannot be maintained and the characteristic chlorotic symptoms of magnesium deficiency manifest themselves. In support of the hypothesis it has been remarked that nitrate deposition levels have continued to rise in recent decades whereas sulfate levels have peaked and declined. Also in support of the hypothesis is the well established fact that excess nitrate will inhibit mycorrhizal associations and reduce winter hardiness. Mitigating against the hypothesis is the sudden widespread appearance of acute magnesium deficiency on soils that have apparently been adequately supplied with it for 300 or more years.

A related soil hypothesis that has not been much heard is that 200 to 300 years of intensive forest management with periodic thinnings and repeated final harvests has depleted soil nutrient reserves to the point that main crop rotation lengths of 100 or more years that were once reasonable are no longer sustainable. Sites that have limitations, such as poor nutrient-supply, high watertables or shallow soils show incremental growth-curves falling off rather suddenly at a particular age rather than declining gradually. Observers of some West German spruce stands feel the stands would be in trouble anyway without air pollution, because they do not seem to possess the vigour required to complete the rotation expected of them. Support for this hypothesis comes from the surprisingly low soil and foliar nutrient levels revealed from recent investigations, and the finding that younger stands can be restored to vigour by applications of fertilizer.

In the direct school of thought there is the very important ozone hypothesis espoused by Prinz and his team at Essen (Krause et al., 1983). This supposes that the high and unexpected levels of ozone present in many remote forest areas of Central Europe (monthly means for summer months are 100 ug m^{-3} with peaks at 500 ug m^{-3}) damage the cuticles of a tree's foliage, permitting a subsequent leaching out of mineral nutrients and other food materials by acid deposition. Much experimentation supports this hypothesis, but growth-chamber foliar symptoms are not always similar to field symptoms and it is not always possible to demonstrate experimentally the combined ozone/acid deposition effect. Further support for the ozone hypothesis, however, comes from recent weather patterns. The summers of 1976, and to a lesser extent 1982 and 1983, were exceptionally sunny and dry. Under such conditions ozone concentrations could be expected to be appreciably greater and the drought stress on mountain soils more extreme. Recent years, therefore, could have embodied the catalytic effect necessary to initiate decline,

but it is clear that many of the other stresses could have been acting too. A further atmospheric hypothesis is that there is as yet some unidentified organic compound causing the decline, within the very large total of organic substances emitted into the atmosphere.

In summary, then, a number of apparently discrete hypotheses have been proposed to explain the forest decline phenomenon of Central Europe. Very recently, the phenomenon has been looked at more analytically and 1985 figures show the level of dieback to be stabilizing and less than previously thought if the lower and more questionable categories of needle loss are excluded. Each decline situation is the result of multiple stress, but the constellation of factors making up each multiple stress situation varies. Synchronizing factors acting directly and indirectly could be the dangers of 1976, 1982 and 1983, the cold winter of 1984/85, and other air pollution characteristics.

4.7.3. APPLICABILITY OF THE CENTRAL EUROPEAN HYPOTHESES TO ELSEWHERE

Some observers have tried to extrapolate the Central European experience and hypotheses to Scandinavia, the Appalachians and Canada. There are good reasons for supposing that the symptoms seen in southwest Sweden and in the Vosges of France are not dissimilar to Central Europe. These are both situations experiencing similar climate trends where air pollution has some of the same characteristics, but for southwest Sweden not at such intensive levels. In southwest Sweden there is a strong suggestion that forest soils have increased in acidity over the 1927 to 1983 period (Hallbacker and Tamm, 1985) by amounts not explainable other than by air pollution effects. Both soil and atmospheric processes could be involved and here we see the inter-relatedness of hypotheses rather than their discreteness.

For the Appalachians numerous critical comparisons have been made to the Central European situation. A particular cause for concern is that Appalachian growth rates have fallen off in the past 20 to 30 years, bearing a striking resemblance to the extremely few German data available (Schroter, 1985). For the Appalachian situation, however, there are several confounding historical factors that would make it hazardous to assume that air pollution has been the sole cause, appreciable though air pollution levels of some localities are.

For central Sweden and the main Boreal and Mixedwood Regions of eastern Canada there are no discernible growth disorders attributable to air pollution. The hypotheses are applicable only as possible mechanisms should pollution and other conditions attain European characteristics. In the absence of clear changes in growth or soil properties in the Canadian forest attributable to regional air pollution, the difficulty would lie in isolating incipient pollution effects from those of a cyclical nature associated with normal forest growth processes. The exception, of course, is the sugar maple situation where there are some similarities to Europe. A fundamental difference here, though, lies in the way Canadian sugar maple is managed compared with European forests.

4.8. KNOWLEDGE GAPS - NEW RESEARCH DIRECTIVES

Other sections in this Assessment describe the various ways whereby air pollutants may impair components of the terrestrial ecosystem. It would be inappropriate in this section to repeat the individual assessments conducted but, in general terms, it is fair to say that our degree of understanding for specifying environmental objectives is much more advanced in the case of the direct effects of individual air pollutants than it is for either indirect effects or the regional scale pollutant mixtures that occur in eastern Canada.

For regional air pollution, the impact on terrestrial ecosystems is complex and poorly understood. Only very little knowledge is available on effects, their causes and possible mitigative practices particularly in the forest system. Specifically, studies are required in the following areas:

4.8.1. DIRECT EFFECTS

1. Research on the physiology and biochemical effects of acid rain needs to be conducted in a number of areas with continued emphasis on effects leading to changes in growth and yield.

2. In agriculture, the relationships between simulated acid rain acidity and plant sensitivity must be investigated and new cultivars screened to prevent the introduction of acid sensitive varieties into high deposition areas.

3. Research into the mechanisms of pollutant interaction particularly as they relate to the interaction of acidic deposition and other pollutants on such processes as cuticle formation and integrity, nutrient leaching from foliage, photosynthesis and respiration, water relations and more complex phenomena such as insect and disease resistance.

4. The role of environmental conditions in influencing pollutant response is a critical component and needs to be investigated as part of dose/response studies.

5. Ozone has been implicated as a contributing or predisposing factor in tree response and it is of paramount importance that both our monitoring efforts and mechanistic studies be increased.

6. Forest decline in Canada has been seen in sugar maple stands in Ontario and Quebec. Research has implicated air pollution but there is no conclusive link. This is clearly an area that needs to be investigated to the fullest.

4.8.2. INDIRECT EFFECTS

1. Studies on the effects of wet and dry deposition on element budgets and soil-weathering processes, especially in respect of normally acutely acid boreal and mixedwood forest soils need to be carried out.

2. Effects studies of wet and dry deposition on the biological and chemical characteristics of forest soil organic horizons need to be continued.

3. The influence of wet and dry deposition on soil element release and toxicity, especially in relation to toxicity in the soil to rootlets, mycorrhizae, and microorganisms; and toxicity in the percolates and drainage waters to stream and lake water quality needs to be resolved.

4. Continue studies on the effects of wet and dry deposition on nitrogen, sulfur and phosphorus cycles, especially their inorganic / organic transformations.

5. Determine the effects of wet and dry deposition in relation to concepts of reversible and irreversible changes in soil characteristics, absorption and complex formation.

6. Examine the fate of deposited potentially toxic elements (e.g. lead, cadmium, mercury, etc.), in relation to soil biological processes and soil fertility.

4.8.3. NEW DIRECTIONS

New directions in research are occurring in some of the above areas but in the forest sector the most significant change has been away from a simplistic concentration on wet acid sulfate deposition. There is increasing concern with wet acid nitrate deposition, with ozone and volatile organics, with the deposition and accumulation of potentially toxic elements, and especially with the concepts of multiple stress and the effects of air pollution in the context of the demands of management practices.

No longer is it adequate to develop management practices in isolation from the effects of air pollution; neither can the effects of air pollution be understood if the demands of management practices or the effects of climatic characteristics are ignored. A holistic approach to forest ecosystems is required that calls for an understanding of atmospheric - forest-soil interactions if the optimum management and protection of forest resources is to be assured.

4.8.4. FOREST DECLINE

Forest declines are dramatic and complex events. Past investigations have taught us that a multitude of factors may be involved in precipitating the decline. This often results in an incomplete resolution of the factors that are involved in the decline, even after a number of years of concentrated effort. The current forest decline situation in Europe is a perfect example of this phenomenon.

In Canada the decline syndrome is neither acute nor extensive but specific concerns have been raised with respect to sugar maple decline in Ontario and Quebec. Research to date suggests that air pollution might be involved but there is no conclusive link. This is clearly an area that needs to be investigated to the fullest.

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